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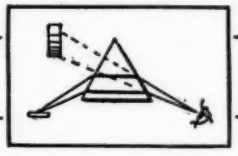

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Journal of the
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The Use of Iron Lines as Intensity Standards

G. H. DIEKE AND H. M. CROSSWHITE
Johns Hopkins University, Baltimore, Maryland
(Received June 1, 1943)

Groups of iron lines with relative intensities independent of excitation are proposed to serve as intensity standards for rapid and reliable plate calibration. One such group between 3140 and 3240A has been tested under a great variety of conditions and found to be satisfactory for this purpose. Lines of Fe I selected at random in general have their relative intensities changed much more by self-reversal than by changes in excitation. A general quantitative study of self-reversal was made which allows an estimate of the degree of self-reversal of any line under given conditions. Weak or moderately strong lines coming down to all but the lowest levels are free from self-reversal under the conditions at which arcs or sparks are usually operated.

§1

RELIABLE calibration of the photographic plate is an absolutely essential prerequisite for all photographic intensity measurements. No ideal method for this seems yet to have been devised. This is particularly true for analytical spectroscopy where, besides great reliability, also ease of operation and speed are required, particularly now when sufficiently trained operators are often unavailable.

One of the commonly employed methods which uses the rotating step sector, besides being subject to difficulties on account of the stroboscopic effect, may introduce errors because of remnants of the intermittency effect which is usually taken to be negligible if high enough speeds of rotation are used, although this has been proved only for a few very special conditions. Recent results in our own and other laboratories[1] have indicated that under the conditions usually employed its effects may not be completely neglected. Besides, this method requires delicate adjustments which easily get out of order and are not easily made by the inexperienced. Another method of plate calibration with the help of the inverse square law requires a light source of small dimension which stays absolutely constant in intensity, which is not easily obtained. Besides, this method is too time-consuming to be used regularly for routine measurements, and diffraction effects may be troublesome. Similar difficulties or inconveniences are attached to most of the other methods proposed for plate calibration.

A rather obvious method of using the intensity ratios of lines in a spectrum like the iron spectrum under constant conditions for plate calibration seems to have been used in various laboratories, although no published reports have come to our attention. The intensity ratios of a selected group of iron lines is measured first with one of the other methods (primary calibration) and these ratios can then be used for further routine operation as long as conditions are rigorously kept constant.

[1] H. H. Grossmann, R. A. Sawyer, and H. B. Vincent, J. Opt. Soc. Am. **33**, 183 (1943). R. A. Sawyer and H. B. Vincent, ibid. **33**, 247 (1943). The latter paper appeared while the present article was in press.

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Whenever the conditions are changed, a new independent measurement of the original lines must be made.

Except for this last difficulty, the use of selected iron lines for plate calibration is especially convenient, particularly for iron and steel analysis where the iron spectrum is necessarily present and then no extra work needs to be done for plate calibration.

Theoretical considerations show that there must be in a spectrum like the iron spectrum groups of lines the relative intensities of which should be entirely independent of the excitation conditions. If such groups of lines can be employed for plate calibration, they can be used without any further precautions once they have been measured in one laboratory, as their relative intensities must be independent, within very wide limits, of the light source employed, the conditions under which it is operated, the spectrograph used, and any other factor which might be varied. The establishment of such groups of lines, the measurement of their relative intensities, and an investigation of their constancy under varying conditions have been undertaken in the spectroscopic laboratory of the Johns Hopkins University and the present paper is a report on the first results. We restrict ourselves to the iron spectrum, although the method is equally well applicable to any other spectrum provided it is rich enough in lines.

§2. CAUSES FOR INTENSITY VARIATIONS

The relative intensities of two spectrum lines produced in the spectrum of a pure element are chiefly influenced by the following two causes: 1. Excitation conditions; 2. The physical surrounding of the light source which produces self-reversal and similar effects.

Other effects enter in if the light source contains a mixture of several elements which, however, can be left out of consideration for our present purpose.

Elimination of the Influence of Excitation Conditions

As every spectrum line results from the transition between an upper and lower level, and the transition probabilities are not very sensitive to external influences, the excitation of the upper level determines the intensity of the line. Lines coming from the same upper level are entirely independent of the excitation conditions, whereas lines which come from widely different levels are strongly influenced by the excitation even though they may have practically the same wave-length. Lines which come from a group of levels lying very close together will for all practical purposes behave as lines from the same upper level. When we find, therefore, a group of lines coming from a set of upper levels very closely lying together, we can be confident that the relative intensities of these lines will not be influenced by the excitation conditions. If these lines lie besides in a narrow wave-length interval, their photographic intensity cannot be affected by any other factor except possibly self-reversal. It is not difficult to find many groups of such lines in the iron spectrum. However, before we know whether we can use them for plate calibration, we must first investigate the influence of self-reversal on such lines.

Effect of Self-Reversal

The emission lines are produced near the center of an arc or spark. Surrounding this center is a cloud of metal vapor through which the light must pass. In this passage a line can be absorbed if the vapor cloud contains atoms in the lower state of this particular line. The more atoms of this kind are present and the stronger the line is, the more the line will lose in intensity by absorption. This kind of absorption is called self-reversal, as the emission line is broadened in the center of the arc, but because the vapor pressure of iron is lower where absorption takes place, the absorption line is narrower and, therefore, the line appears under high dispersion as a broadened line with the center sharply cut out. If the resolution of the spectrograph is not sufficient to show this, the line appears merely weakened.

As under all conditions under which light sources are operated most atoms in the surrounding vapor cloud will be in the normal state, those lines having the normal state as lower level will be most strongly absorbed, a state of affairs with which every spectroscopist is familiar. Under special conditions it may be possible that no other lines but these will be appreciably self-reversed. However, usually there will be also

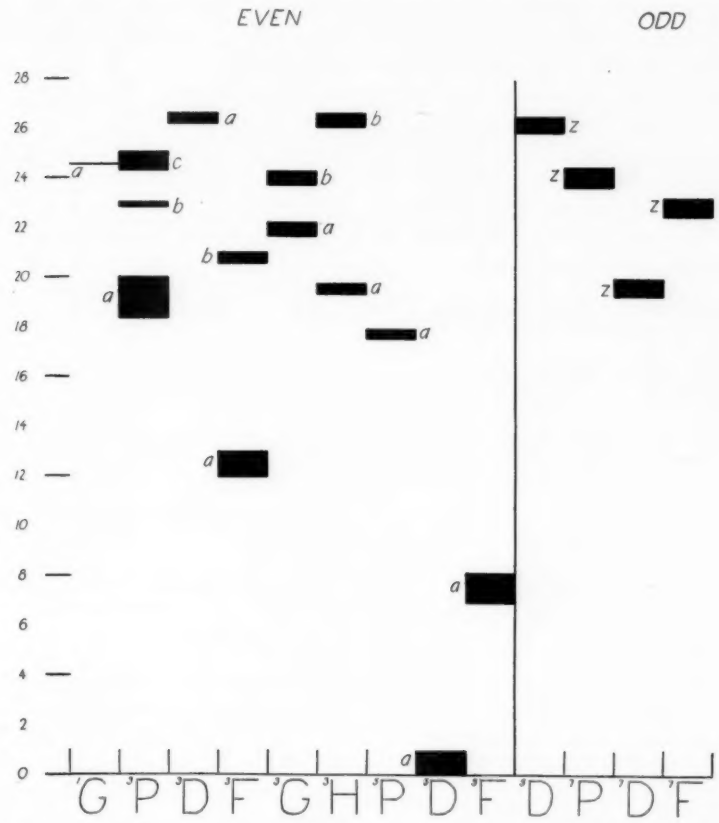

FIG. 1. Diagram of the low-lying energy levels of Fe I. The width is the total multiplet width. Scale in 1000 cm^{-1}.

atoms in the next higher states in diminishing number as the energy of these states increases.

A line which is subject to strong self-reversal is unsuitable as intensity standard, for the exact amount of self-reversal depends on the extent and density of the surrounding cloud, quantities which may be strongly influenced by such uncontrollable effects as an opened door or the breathing of the observer, besides the current in the light source which determines the temperature of the electrodes.

Lines suitable for intensity standards must be, therefore, homogeneous groups of lines, i.e., lines which are excited in the same way, and besides they must be free from self-reversal. A selection of such lines is greatly facilitated by a knowledge of the theoretical structure of the spectrum. The iron spectrum has been very thoroughly analyzed by various investigators. The earlier results are most completely given by Burns and Walters.[2] The analysis has since been augmented considerably by Russell and Sitterly, and we are very grateful to Professor Russell and Mrs. Sitterly for putting at our disposal a copy of their very extended tables containing the results of their analysis of the iron spectrum.

In order to select lines which will show the minimum self-reversal, we may look at a diagram of the lower levels of the iron spectrum (Fig. 1). On the left of the diagram are the even states and on the right the odd states. All even states below z^7D, the lowest odd state, are metastable, i.e., once the atom finds itself in such a state it cannot leave it by ordinary dipole radiation and will be

[2] K. Burns and F. H. Walters, Pub. Allegheny Obs. **6**, 159 (1929); **8**, 43 (1931).

removed from it chiefly by collisions. The number of atoms in these metastable states will, therefore, be relatively larger than the number in non-metastable states, with everything else equal. For this reason we have selected as lines best suited for a first trial a group of lines lying in the region between 3100 and 3300A, having the lowest odd z^7D state as lower level. This region is very suitable, as many lines important for analytical spectroscopy lie in or near it.

§3. MEASUREMENT OF INTENSITIES UNDER VARIED CONDITIONS

A thorough experimental investigation of the behavior of such a selected group of lines under as varied conditions as possible seemed to be indicated first. Results obtained here can then be transferred to similar groups in other parts of the spectrum.

Practically every method of intensity measurement gives the logarithm of the intensity more readily than the intensity itself, and the logarithm has a constant error of measurement. Moreover in most applications the logarithm is needed. Therefore, there seems to be no reason to give the intensity values themselves. This agrees with the practice of the astronomers, who give the intensities of stars in magnitudes which are equal to the log I (multiplied by a factor $-\frac{1}{4}$).

The intensities of all the lines in the 3100–3300A interval were measured in a number of spectra under the following conditions:

d.c. arc, current 2, 4, and 8 amp.
High voltage a.c. arc, current 2.5 amp. and 5 amp.
Condensed spark with low and high self-inductance.
Carbon arc with Fe as impurity.

The plates were calibrated with the inverse square law by taking a number of exposures of a small Hg-discharge at varying distances from the slit.

Table I gives an extract from the results.[3] The homogeneous group ending on the z^7D state is

TABLE I. Log I values of Fe lines under various light source conditions.

		d.c. 4 amp.		d.c. 8 amp	a.c. arc	Spark	Classification†
	(f)	(g)	(i)	(c)			
3116.6	1.45	1.45		1.20	1.44	1.52	$a^5F_1-x^5D_2$
19.5			1.05	1.05	1.09	1.13	$a^5H_5-z^5G_4$
20.4			1.00	1.00	1.05	1.12	$a^5H_4-z^5G_3$
25.6		1.62		1.38	1.61	1.59	$a^5F_2-x^5D_3$
26.1			.93	1.01	.93	1.08	
34.1		1.43	1.35	1.20	1.41	1.28	$a^5F_3-x^5D_4$
51.3		1.19	1.19	1.24	1.14	1.30	$a^5G_4-y^5H_5$
*53.2		1.07	1.09	1.11	1.10	1.12	$z^7D_3-f^5F_4$
56.2			.92	.97		1.05	$z^5D_2-z^5D_3$
*57.0		1.30	1.29	1.29	1.30	1.29	$z^7D_4-e^7G_5$
*57.8		1.16	1.16	1.18	1.17	1.17	$z^7D_2-e^7S_3$
*60.6		1.36		1.34	1.36	1.36	$z^7D_4-e^7F_4$
*61.9		1.15	1.15	1.15	1.15	1.28	$z^7D_5-e^7G_6$
*75.4	1.38	1.39	1.38	1.38	1.38	1.39	$z^7D_5-e^7F_4$
*78.0	1.27	1.29	1.29	1.29	1.27	1.29	$z^7D_5-f^7D_4$
80.2	1.66	1.66		1.56	1.64	1.74	$z^7D_2-e^7F_4$ Fe II line overlapping
84.9		1.48		1.11	1.46		$a^5D_2-z^5F_2$
91.6		1.54		1.13	1.50	1.31	$a^5D_4-z^5F_4$
92.8		1.49		1.49	1.50	1.71	$z^7D_1-e^7F_2$ Fe II overlapping
93.8			<.8	<.9	<.8	1.94	Fe II
96.0			1.07	1.07	1.05	1.84	Fe II+Fe I
99.5	1.63	1.63		1.51	1.60	1.56	$z^7D_4-f^7D_4$ $a^5D_1-z^5F_2$
*3200.4	1.68	1.67		1.62	1.68	1.69	$z^7D_3-e^7F_3$ $z^7D_2-e^5S_2$
*05.3	1.60	1.61		1.59	1.60	1.61	$z^7D_4-e^7F_1$
*15.9	1.64	1.64	1.63	1.62	1.64	1.67	$z^7D_2-f^7D_2$
*17.3	1.50	1.50	1.49	1.51	1.50	1.51	$z^7D_5-e^5D_4$
*22.0	2.06			1.81	2.05	2.07	$z^7D_5-f^7D_5$
*25.7	2.16			1.85	2.16	2.17	$z^7D_5-e^7F_6$
*39.4	1.77	1.77	1.77	1.71	1.78	1.78	$z^7D_4-e^5D_{4,3}$
*44.1	1.73	1.73	1.73	1.69	1.72	1.73	$z^7D_4-e^7P_3$

† After Russell and Sitterly.

marked by an asterisk, and it is seen that these lines do not change their intensity in any of the spectra and will, therefore, be suitable as standard lines. In contrast with these lines is the majority of other lines which vary widely under different conditions, either because they are responsive to differences in excitation, as e.g., 3193.8 or 3196.0, or are affected by self-reversal, as 3125.6, or both.

Small systematic differences in the homogeneous group which are apparent on closer inspection are not real but due to changes in plate contrast with wave-length, which have been eliminated in later measurements.

The experiments summarized in Table I show, therefore, that although the relative intensities of a group of iron lines selected at random may vary strongly with changes in the light source conditions, the lines in the homogeneous group selected maintain a constant intensity ratio.

While these measurements prove that the intensities of this particular group are independent of the light source conditions, it is desirable to investigate in general what cause is chiefly responsible for the intensity changes in other groups of lines. In this way it will be possible to

[3] Imperfect control of the primary calibration in the earlier experiments has caused the values of the intensities given in Table I to be slightly different from later values when these imperfections had been eliminated. This, however, has no influence on the comparison of the values taken under different conditions. Only the intensity scale used is different from the true one.

select other non-variable groups of lines with greater confidence and also to avoid those light source conditions which are likely to affect the intensities most strongly.

If a group of lines contains both lines of Fe I and Fe II, it is obvious that the electrical excitation conditions are the greatest single factor governing the relative intensities. This is well known, and no special measurements are necessary to establish this fact.

If, however, the group contains, e.g., only Fe I lines, then contrary to the general belief, unless extreme conditions are maintained which do not occur in any of the commonly employed light sources, the excitation conditions have relatively little influence and the intensity ratios are governed predominantly by self-reversal. A quantitative study of self-reversal is, therefore, very essential for any use of the relative intensities of standard lines.

§4. EXPERIMENTAL STUDY OF SELF-REVERSAL

For a quantitative study of self-reversal, a study of the intensity changes with a wide slit is most convenient, which will give the total weakening of the line, whereas a quick qualitative survey can be made most easily by observing the actual self-reversal with a narrow slit and high resolution. We employed both methods, using the fourth order of a 21-ft. Wadsworth mounting with a resolving power of approximately 300,000 for the qualitative work, and the second order of the same spectrograph for the quantitative part. The results of both ways of approach were always in complete agreement.

The influence of self-reversal on line intensities has long been recognized as important. However, in most previous investigations,[4] the interest was centered chiefly on demonstrating whether the theoretical rules for intensities in multiplets would hold or not. Therefore these investigators usually were content to select light sources which showed a minimum amount of self-reversal without making a study of self-reversal itself. Harrison,[5] however, did investigate the dependence of self-reversal on the intensity of the lines in titanium multiplets. He used the theoretical values for the unreversed intensities. In general, and particularly in the Fe spectrum, the theoretical values of multiplet intensities do not agree very well with the observed ones. The agreement can be expected to be good only for the low levels where self-reversal is very big, and, therefore, theoretical intensity relations are of little practical value for accurate plate calibration.

Theoretical Considerations

At the present stage a very simple mechanism of self-reversal is quite adequate. We assume that the line is emitted at the center of the light source with an intensity I_0 and traverses then an optical path of length d.

$$d = \int N_r dr,$$

where N_r is the number of atoms per unit volume at a distance r from the light source capable of absorbing the particular line, i.e., atoms in the lower state of the emission line. The intensity far from the light source is then

$$I = I_0 e^{-ad},$$

where a is the absorption coefficient per unit number of absorbing atoms. This is proportional to the transition probability, which in turn is proportional to the emission intensity I_0:

$$a = \alpha I_0,$$

for a limited wave-length region α contains only general constants.

$$I = I_0 \exp(-\alpha d I_0).$$

This formula holds only as far as the effects due to the pressure broadening of the line are neglected, and can be written, if $x = \log I_0$,

$$\log I/I_0 = -\alpha d e^x. \qquad (1)$$

I and I_0 can be measured except for a constant factor which shifts all the logarithms by a constant amount. In order to obtain I_0, it is necessary to use a light source free from self-reversal, i.e., a light source where the absorbing cloud is absent.[4,5] As the cloud is kept together by the air, employment of a vacuum arc will remove self-reversal. Another, and usually simpler way to

[4] See, e.g., R. Frerichs, Ann. d. Physik **81**, 807 (1926); J. B. van Milaan, Zeits. f. Physik **34**, 921 (1925).

[5] G. R. Harrison, J. Opt. Soc. Am. **17**, 389 (1928); G. R. Harrison and H. Engwicht, J. Opt. Soc. Am. **18**, 287 (1929).

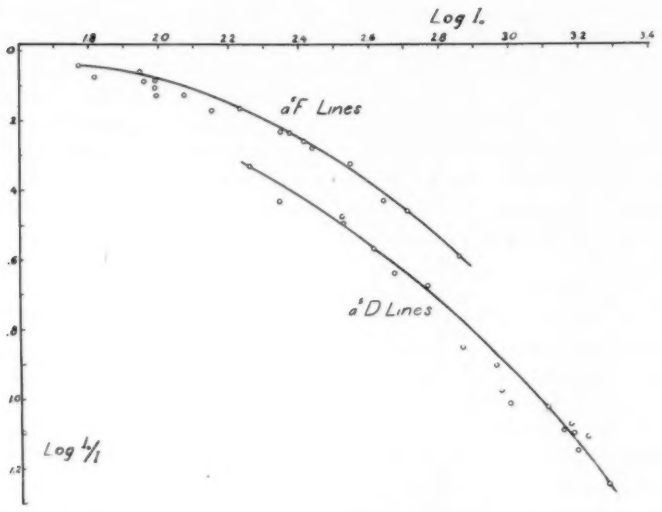

FIG. 2. Self-reversal of Fe lines between 2900A and 3100A ending on the a^5D and a^5F levels. (d.c. arc, current 2 amp.)

obtain the same result is to use as electrodes some other material which contains iron only as an impurity. The diffusion equilibrium maintains a cloud of a given density. If iron is present as an impurity, the total amount of iron in the cloud is very much smaller than if the cloud consisted only of iron, and self-reversal is cut down in the same proportion.

As the emission line itself is dependent for its existence on a cloud at the center of the light source, the absorbing cloud can never be completely eliminated. However, it can be reduced to such an extent in most cases that it will no longer cause any appreciable self-reversal. Naturally any device to cut down self-reversal also will cut down the absolute intensity of the line, but will increase its sharpness.

In our experiments we used carbon electrodes which contained iron as impurity to obtain I_0. For longer wave-lengths where the bands associated with carbon give a troublesome background, we used an alloy of copper with about $\frac{3}{4}$ percent iron. A direct examination in the fourth order showed no self-reversal in these sources.

We can apply (1) now to a group of lines which have a common lower level, for which the optical path length d is the same. This applies with great approximation also if the lower levels are not identical but lie close together as the components of a multiplet.[6]

The reduction in intensity of all lines of this group is then determined only by the original intensity I_0 of the line.

The experimental confirmation of this is shown in Figs. 2–6, where $\log I/I_0$ is plotted against $\log I_0$ for lines between 2900 and 3100A ending on the a^5F or the a^5D level, the two lowest iron levels. For each of the two groups of levels, the points lie on one smooth curve.[7]

The exact shape of the curve, particularly whether it agrees with the theoretical equation, is not very important, although it is approximately of the required shape, for the broadening effect will cause deviations from the theoretical expression. However, as these broadening effects depend chiefly on I_0, the result will again be a smooth curve representing self-reversal as function of I_0. Another uncertainty is due to the fact

[6] A simple consideration shows that in calculating the optical path length d we must disregard the *a priori* probability $(2J+1)$ in the number of atoms. This factor is taken care of in I_0. This can be easily seen if the J degeneracy is first removed (e.g., by a magnetic field).

[7] The scattering of the points in general is not due to accidental errors of measurement, but due to the fact that a fairly large wave-length interval was covered for which both the sensitivity and the contrast of the plate changed, which changes were not taken into account in the plate calibration.

that the value of I_0 cannot be exactly measured, as some trace of self-reversal is probably left in any light source, which uncertainty may affect particularly the strong lines.

§5. SELF-REVERSAL AS FUNCTION OF THE LOWER STATE

In the vapor cloud surrounding the light source, the largest number of atoms will be in the ground state a^5D, and accordingly we must expect the strongest self-reversal in those lines which have the normal state as lower level. As the energy of the state increases, its presence in the cloud becomes increasingly less frequent, and, therefore, those lines ending on the more highly excited states should show less self-reversal. This is exactly what is observed (see Figs. 2 and 3). If the cloud is in thermal equilibrium, the relative numbers of atoms are given by the Boltzmann factor

$$e^{-E/kT},$$

which inserted in (1) gives

$$\log I_0/I = bI_0e^{-E/kT} = \beta e^{x-(E/kT)}; \quad x = \log I_0, \quad (2)$$

where b and β are other constants independent of I_0 and the state. Two lines having the same I/I_0 must satisfy the condition

$$x' - x'' = (E' - E'')/kT.$$

This is independent of I_0, which means that the curves for the various levels should be parallel to each other. This condition is satisfied by the experimental curves and illustrated by Figs. 2 and 3. It is independent of the question of whether there is temperature equilibrium or not.

In the case of temperature equilibrium, (2) can be used to calculate the temperature. In the example in Fig. 2, we would get $T = 16{,}800°$, which shows that there can be no temperature equilibrium. Measurements with other line groups, especially groups of Fe II, also show that in those parts of the light source where self-

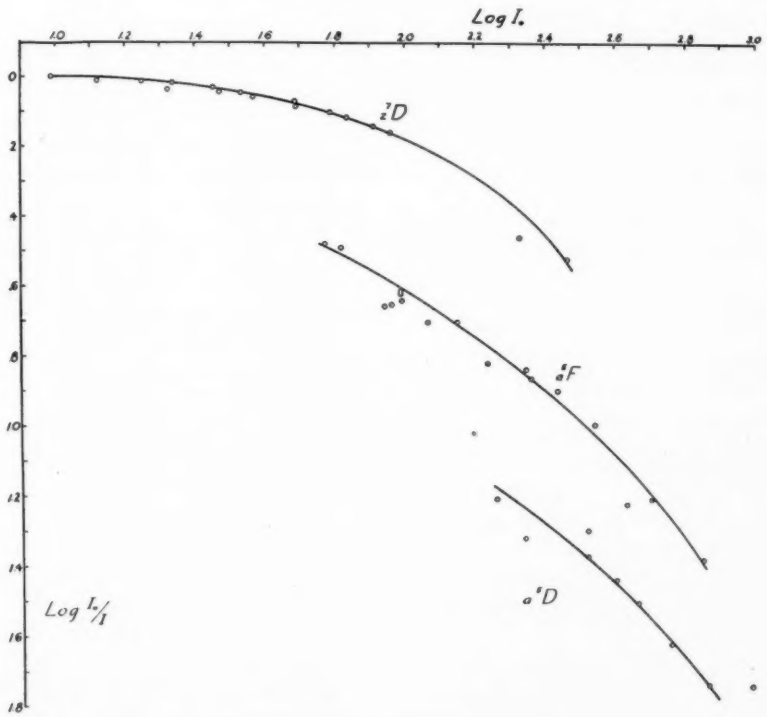

FIG. 3. Self-reversal of Fe lines in 8-amp. d.c. arc.

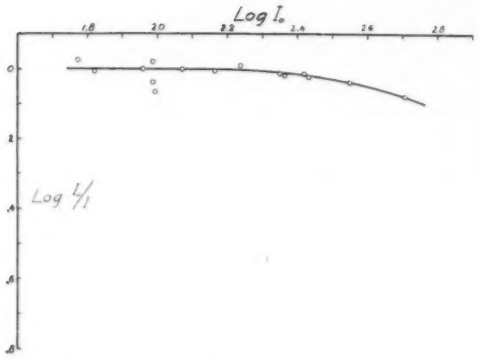

FIG. 4. Self-reversal of a^5F lines in 2-amp. d.c. arc.

reversal occurs, no temperature equilibrium between the various excited states can exist.

Such experiments refute the contention of Levy[8] that the relative intensities are determined only by some kind of effective temperature. The excitation and self-reversal are two independently varying parameters affecting different lines in different ways. We have made extensive studies on this point which will be published in a later paper. In this conclusion we are in agreement with results of Grossman, Sawyer, and Vincent,[1] obtained in quite a different way.

§6. DEPENDENCE OF SELF-REVERSAL ON TYPE OF LIGHT SOURCE

The self-reversal curves depend very much on the type of light source used. In the d.c. arc the higher the current density, the higher the electrode temperatures, i.e., the greater the density of iron atoms in the cloud. By a comparison of Figs. 2 and 3, we see that the self-reversal is much larger in the 8-amp. arc than in the 2-amp. arc, and many other measurements in arcs of varying currents show the same behavior. The a.c. arc at 5000v shows not much difference from the d.c. arc (Fig. 5). Its self-reversal is somewhat higher than that of a d.c. arc of the same current, which is in agreement with the fact that the electrodes are hotter. The spark has a slightly smaller degree of self-reversal than the arc, which also is what is to be expected.

It is almost impossible to get the same self-reversal curve twice, even if great care is taken to have conditions exactly the same both times. This is illustrated by a comparison of Figs. 2 and 4, which were both taken with a 2-ampere d.c. arc. In Fig. 4 there is no appreciable self-reversal for log I values up to 2.3, whereas the same lines are very strongly self-reversed in Fig. 2. This behavior is not surprising, because of the sensitivity of the vapor cloud on which self-reversal depends on slight air currents. To make sure that air currents are the chief cause for the differences, we took pictures under identical conditions, one with the light source left to itself, and one with a fan blowing mildly at the light source away from the slit (Fig. 6). The reduction of the self-reversal is quite marked in the spectrum with the fan blowing. If the fan blows toward the slit so that the cloud is blown mostly into the light path, the degree of self-reversal becomes much larger. Similar results apply to the d.c. arc. This behavior of self-reversal explains some of the erratic results which are sometimes obtained with intensity measurements in atomic spectra, especially with strong lines.

§7. CONDITIONS FOR MINIMUM SELF-REVERSAL

If intensity measurements are to be used for plate calibration, or the determination of concentrations in analytical spectroscopy, or almost any other purpose, self-reversal is a severe drawback, particularly because of its erratic behavior. It should therefore be eliminated as much as possible. The figures show amply that for strong lines the effect of self-reversal is no small correction. For some lines we have found $\log I_0/I=2$ which means that 99 percent of the light of those lines is lost by self-reversal. It is therefore important from a practical point of view to ascertain the conditions under which self-reversal is a minimum. The following rules are self-evident from the preceding discussion:

1. Avoid very strong lines.
2. Avoid lines ending on the normal state or other low-lying levels of the atom.
3. Do not use high currents.
4. Place the light source in an air current blowing away from the slit.
5. Use light sources which prevent the formation of an extensive cloud (e.g., at reduced pressure).

[8] S. Levy, J. App. Phys. **11**, 480 (1940).

A comparison of Figs. 2–4 shows how far the elimination of self-reversal has been achieved for the lines studied here. It also allows a prediction of the self-reversal for any line with known classification.

The figures show that with given light source conditions, the absolute intensity I_0 is the greatest single factor governing the self-reversal, and next comes the lower state of the line. The curves approach for large intensities a slope of 45°. This means that for that intensity range the observed intensity of the line is independent of its real intensity I_0. Such a state of affairs must be expected if there is equilibrium between emission and absorption.

The figures also indicate that under conditions prevailing in the customary light sources, the strong lines must be expected to be always strongly self-reversed and unsuitable as intensity standards. This is due to two causes, first, because of their intrinsic intensity, and secondly, because the strong lines generally originate from the lowest levels and are, therefore, subject to the strongest self-reversal.

On the other hand, the lines ending on the z^7D level suggested as intensity standards in the present paper are safe from self-reversal under all but the most severe conditions. Figure 3 shows that even in an 8-amp. arc, lines of this group with an intensity lower than 1.3 show no self-reversal. The other extreme (Fig. 4) shows that even as unfavorable lines as those ending on the a^5F state are free from self-reversal for log I_0

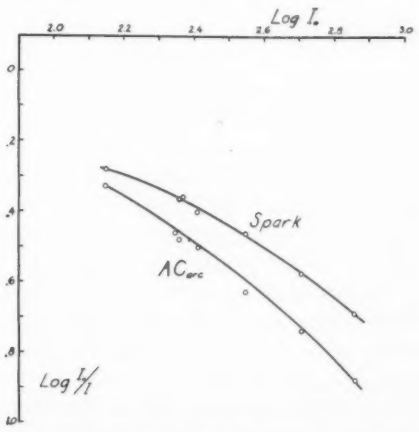

FIG. 5. Self-reversal of a^5F lines in a.c. arc and spark.

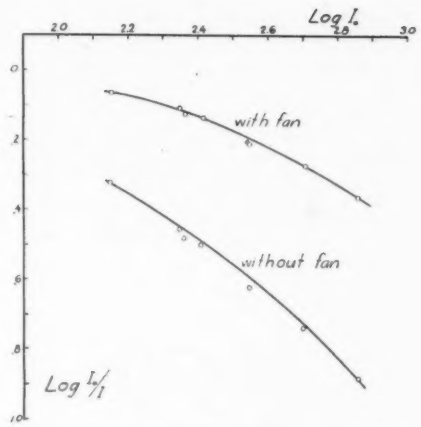

FIG. 6. Influence of air current produced by fan blowing away from slit on self-reversal of a^5F lines.

below 2.3. Figure 2 shows the state of affairs under average conditions when no special precautions are taken but excessively high currents are avoided. A comparison with Fig. 3 shows that we may expect that all standard lines (ending on z^7D) may be expected to be safe from self-reversal for log I_0 smaller than 2. This means that all these lines may be used as intensity standards without special precautions except the two strongest ones. Our experience in using these lines for practical plate calibration has entirely corroborated this. All lines of this group give consistent results except the two strong lines.

§8. PRACTICAL APPLICATIONS

A. The first and most obvious practical purpose for which these standard groups of lines may be used is local plate calibration which would make any rotating sector or similar device unnecessary.

B. The problem of measuring the relative intensities of lines separated by a large wave-length interval has always been particularly difficult, especially in the ultraviolet. According to the discussion in §4, groups of lines may be selected so that self-reversal is only a function of the true intensity. For this it does not matter if the lines are in entirely different wave-length regions. Conversely, by measuring the self-reversal of groups of Fe lines in different parts of the spectrum, their true relative intensities can be determined. By using these lines as intermediates,

the relative intensities of groups of lines in all parts of the spectrum may be determined which are free from self-reversal and independent of excitation.

C. Such groups can then be used as standards to eliminate plate sensitivity and the influence of the particular instrument in any problem in which the intensities of widely separated lines are to be measured. This procedure requires a minimum of equipment and effort, once these standards are established.

D. In particular, this may be applied to problems in analytical spectroscopy where suitable lines of all the constituents cannot be found in a narrow wave-length interval. The only additional requirement is to photograph an iron spectrum on each plate which is to be calibrated.

E. In a spectrum for which the analysis is incompletely known, the self-reversal can be plotted as function of the measured intensity, and several empirical curves obtained resembling those of Figs. 2 and 3. The lines lying on one curve belong to the same lower state and an estimate can be made of the relative energies of the various lower states. Valuable clues can thus be obtained for the classification of the lines. For this kind of help in the analysis of complicated spectra, the self-reversal method is equivalent to furnace absorption experiments, but with a greatly simplified technique.

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Properties of Low Reflection Films Produced by the Action of Hydrofluoric Acid Vapor

F. H. NICOLL AND F. E. WILLIAMS
RCA Laboratories, Princeton, New Jersey
(Received April 9, 1943)

THE use of hydrofluoric acid vapor to produce low reflection films on glass has been reported some time ago.[1] Further work has now been carried out and this paper describes experiments leading to the conclusion that the low reflection film is skeletonized silica. In addition a number of properties of the film are described.

The process consists of exposing the glass to dilute hydrofluoric acid vapor under controlled conditions. Glass so treated is covered with a white deposit which is soluble in water. When this is removed, a hard, insoluble, low reflection film remains on the glass surface. Such hard, insoluble, and low reflection films are only produced in a relatively narrow range of concentrations, although other types which are soft and water soluble, or visibly etched, can be produced over a wide range. Under correct conditions the chemical action consists of selective attack by the hydrofluoric acid vapor. This produces soluble compounds of the metallic constituents of the glass, but at the same time leaves a large portion of the silica unattacked.

Experimental evidence that the low reflection film is composed of skeletonized silica is obtained from chemical analysis, electron micrographs, and observations concerning the chemical solubilities and the refractive index requirements of the film.

In order to make a good chemical analysis about 250 milligrams of material are necessary. When dealing with films about 1000A thick it becomes difficult to remove the film and also requires a very large amount of treated glass to give the desired quantity of material. It was found that it was possible to produce a film about 5000A thick which could be removed fairly readily with a sharp razor blade. Something approaching thirty square feet of window glass was treated in order to obtain the required amount of material. The analysis of the low index film on the glass indicates that it is 95 percent silica, and since the method of sampling may include some

[1] F. H. Nicoll, RCA Review **6**, 287 (1942).

FIG. 1. Electron photomicrograph showing skeleton structure of low reflection film.

residual glass scrapings, the percentage of silica may be even greater.

Since the film is practically pure silica, it must also be skeletonized in order to produce a refractive index of about 1.28 which is necessary to reduce the reflection of window glass to a low value. A calculation using the Clausius and Mosotti law indicates that about 40 percent of a solid silica film must be removed in order to give the required index.

Electron microscope pictures have been made of a small fragment of quarter-wave-length film scraped from a treated sample of window glass. The film can then be observed with fifty kilovolt electrons. A photomicrograph taken on an RCA electron microscope type B is shown in Fig. 1. This illustrates the structure of the film and it can be seen that the holes are between 100 and 200A in size. This is small enough that no appreciable scattering of light will take place and accounts for the reduction in index of refraction by the removal of material.

The film produced by the hydrofluoric acid treatment is insoluble in all common acids. Boiling sodium hydroxide removes the film and it is also removed by hydrofluoric acid solutions. Hydrofluoric acid and sodium hydroxide are known to attack silica, and at the same time there are relatively few inorganic materials which are not attacked by some of the common acids. The observed solubilities are therefore in agreement with other evidence that the film is silica.

A large number of glasses ranging from 30 to 80 percent silica, of varying composition, have now been successfully treated. These glasses have only silica in common. Lead glass, which is readily treated by the old nitric acid leaching method,[2] can also be treated by the hydrofluoric acid vapor process. This feature makes it possible to prepare a sample which shows the advantage of using the latter process. A piece of lead glass ($n=1.6$) was treated on adjacent halves by the two processes to give minimum reflection for green light. If the sample is now viewed in air the vapor-produced film is observed to have much less reflection than the leached film, and to have a red-purple color. This indicates that the refractive index of the vapor-produced film is near the correct value for extinction of green light, *viz.*, $(1.6\times1)^{\frac{1}{2}}=1.26$. Now if the sample is immersed in water the leached film is seen to have the lower reflection and red-purple color. It is thus concluded that in this case the index of the leached film is near that required for extinction of green light, *viz.*, $(1.6\times1.33)^{\frac{1}{2}}=1.46$. These values for the refractive index of the two films are not far removed from those determined by more accurate means.

A glass surface treated by the hydrofluoric acid vapor process tends to lose its properties if oil or grease comes in contact with the surface. It can be cleaned with a damp cloth if the oil has only been present for a few hours; however, after it has remained for a matter of days the full low reflecting properties can only be brought back by washing the glass with soap and water or some grease solvent.

Low reflection silica films of the type described are believed to be more durable than the best evaporated films. They have high resistance to abrasion when properly made and are practically inert chemically. Humidity and salt water tests have no effect on the film or its reflection. The reflection from glass as treated by the hydrofluoric acid vapor process may be as low as 0.2 percent of the incident light and this is the case for both low and high index glasses. The very low scattering in the film insures a correspondingly high light transmission and thus makes the film suitable for optical use where increased transmission is desirable.

[2] F. E. Wright, "Characteristics of optical glass," Ordnance Department, Document No. 2037, p. 76 (1921).

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Halftone Densities

PAUL W. DORST
Department of Lithographic Research, University of Cincinnati, Cincinnati, Ohio
(Received February 13, 1943)

CERTAIN printing processes, such as letterpress and offset lithography, are incapable of printing tone values intermediate between white and black. A complete scale of tones, however, is simulated by "halftone" dots which are too small to be resolved by the naked eye. Variation in tone value is brought about by variation in dot area, the tones becoming darker as the fractional area of the black dots increases from zero to one. The exact relationship between tone value and dot area is not an obvious one, and an understanding of this relationship is helpful in obtaining desirable halftone reproductions.

The optical reflection density, defined as $\log 1/R$, where R is the reflectance or fraction of incident light reflected by a region under consideration, is a suitable measure of tone values in halftone studies as well as in continuous-tone work such as photography. Density differences agree quite well with tone differences estimated by the eye, and suitable commercial instruments are available for reading density values with sufficient accuracy for all practical purposes.

RELATIONS BETWEEN DENSITY OF BLACK DOTS, AREA OF DOTS, AND INTEGRATED DENSITY

The dot area, or fraction of the total area which is occupied by printed ink within a given region of a halftone print, is customarily estimated by craftsmen in terms of eighths or sixteenths, using a magnifier for visual inspection. Thus a "quarter-dot" tint refers to one in which the printed dots occupy one-fourth of the total area. Planimeter measurements on photomicrographs have shown that dot areas of approximately one-half are estimated with fair accuracy by the average craftsman, but that his estimates become less accurate as the dot area approaches zero and one. There seems to be a tendency to confuse linear dimensions and fractional area. Nevertheless, the significance of dot area is realized in the trade, although its exact effect on apparent density is not widely understood.

Another factor affecting the density of a halftone region is the optical density of the printed ink itself. The density of inked areas varies with the character of the paper surface, the characteristics of the ink, and certain other factors. Certain variations in the density of individual printed dots are peculiar to the process used for printing them. On relief or letterpress prints, for example, the dots have sharply defined outlines, and the borders are sometimes more dense than the internal portions of the dots. This result is caused by the squeezing of the ink between the printing plate and the paper, out into the open spaces where no pressure exists, thus leaving a heavier film of ink at the edges. On rough surfaced papers the density difference within the dot is ordinarily less than on smooth surfaced papers, and may not be noticeable at all. Murray[1] has observed that the value of average density within the printed portion of a letterpress dot is equivalent to the density of a solid black ("unstructured") area of the same print.

The boundaries of halftone dots printed by offset lithography are generally not as sharp as those printed by letterpress, and the density is maximum throughout the internal portion of each dot. This characteristic is caused by the transfer of ink both from the lithographic plate to the rubber offset blanket surface, and from the blanket surface to the surface being printed, with uniform mechanical pressure on ink and non-ink areas alike.

An ideal printed halftone dot would be uniform in density throughout its area, and would be bounded by a mathematically sharp line. Halftone prints, either letterpress or offset, seldom approach the ideal so far as the dots are concerned, although the pictorial result may be entirely satisfactory. A study of the density

[1] Alexander Murray, J. Frank. Inst. 221, 721–744 (1936).

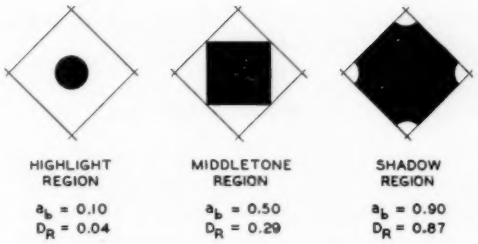

FIG. 1. Unit square areas of regions on a halftone reproduction. Values of D_R are shown for $D_b = 1.4$.

relationship of ideal halftone dots, however, has practical value since the deviation of the actual dots from the ideal is generally not great, and since certain practical relationships are thus brought out. For letterpress prints, the average density may be used in calculations, and for offset lithographic prints, an equivalent area can be employed.

Let us consider a unit square area of a halftone print in black ink on a white background, such as one of the squares shown in Fig. 1. Part of the unit area is covered with black ink, the remainder being white. The apparent tone value of a region including a number of like unit areas will be represented by its integrated density, which is a function of the fraction of incident light reflected by such unit areas. Murray[1] has expressed the relationship as

$$D_R = \log 1/[1-a_b(1-R_b)], \qquad (1)$$

where D_R is the apparent density of the reproduction, a_b is the black dot area (fractional), and R_b is the reflectance of the black portion. Yule[2] has written the same expression, including the reflectance of the white portion R_w as follows:

$$D_R = -\log [a_b R_b + (1-a_b)R_w]. \qquad (2)$$

A simpler expression for practical use, however, is obtained by using absorptions instead of densities. If A_b denotes the absorption of the black portion and A_w the absorption of the white portion, then the absorption of the entire unit area of a reproduction is

$$A_R = a_b A_b + (1-a_b)A_w. \qquad (3)$$

[2] J. A. C. Yule, J. Frank. Inst. **231**, 23–38 (1941).

If the density of the white unprinted paper is taken as zero, as is customarily the case, A_w becomes zero, and Eq. (3) becomes

$$A_R = a_b A_b. \qquad (4)$$

From Eq. (4), the following expression relating D_R, a_b, and the density of the black inked area D_b, is derived:

$$D_R = \log \{1/[1-a_b(1-1/\text{antilog } D_b)]\}. \qquad (5)$$

Equation (5), which is a variation of Eqs. (1) and (2), gives directly the area of dots required for any reproduction density when the printed ink density D_b is known. This expression is not convenient for everyday use, however, and some means of rapid computation is desirable. A graphical method can be employed, or a special slide rule can be constructed for the purpose.

GRAPHICAL SOLUTION

The linear relationship of Eq. (4) lends itself to simple graphical solution. On the chart shown in Fig. 2, a_b is plotted on the horizontal axis, and A_R on the left vertical axis. Conversion of values of A_R to values of D_R is accomplished by laying

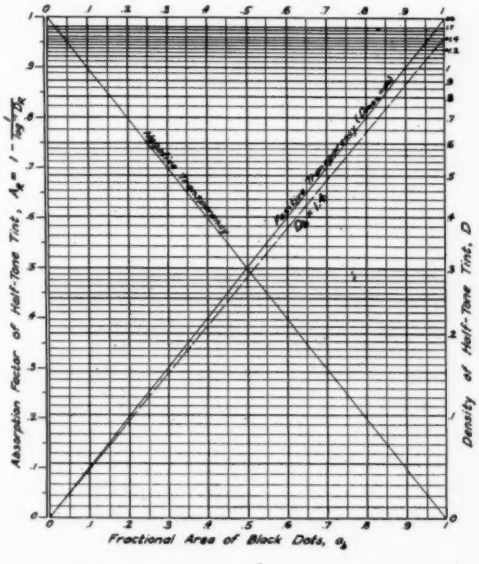

FIG. 2. Densities of halftone tints *vs.* dot areas—uniform absorption scale.

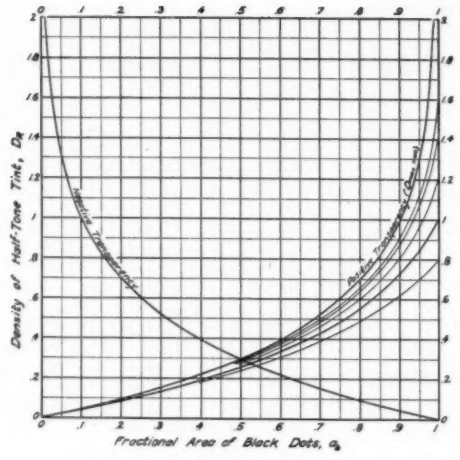

FIG. 3. Densities of halftone tints *vs.* dot areas—uniform density scale.

off a scale of corresponding values of D_R (where $A_R = 1 - 1/\text{antilog } D_R$) on the right vertical axis. Since density values are usually desired, the density scale lines are carried across the graph.

On this chart, a straight line can be drawn to satisfy Eq. (5) for any given value of D_b. When $a_b = 0$, $D_R = 0$, and when $a_b = 1$, $D_R = D_b$. The line is therefore drawn from the value of D_b on the right vertical scale to the origin. The dashed line in Fig. 2 represents the relationship between a_b and D_R for $D_b = 1.4$.

For positive halftone transparencies, the transmission density of the black dots may be assumed to be infinity, and the solid diagonal line marked "Positive Transparency" will give transmission density values of any tone having a fractional black area of a_b. The line marked "Negative Transparency" shows the relation between negative density and transparent dot area, which is equivalent to black dot area on a corresponding theoretical positive. The effect of a change in D_b for any given value of a_b is found by following vertically down from the line representing one value of D_b to the line drawn for another value.

While Fig. 2 is convenient for determining numerical values of density and dot area, these relations are better illustrated visually in Fig. 3, in which the density scale is uniform. On this plot, the straight lines of Fig. 2 become curves, each terminating on the vertical density scale in the value of D_b it represents.

SLIDE RULE

A simple slide rule may also be constructed to solve Eq. (5). Such a rule, shown in Fig. 4, consists of two scales "a" and "D," "a" representing values of a_b, and "D" representing values of both D_b and D_R. The slide bears the "a" scale, which is logarithmic and has two cycles, values from 0.01 to 0.1 being laid off along the lower edge and 0.1 to 1.0 along the upper edge. The body of the rule carries the "D" scale, which is actually a logarithmic scale of absorption factor A_R, but calibrated with the corresponding values of density. The rule thus performs the operation $A_R = a_b A_b$, while values of D_R and D_b are read off directly.

To use the rule, the index (1) on scale "a" is set opposite the value of D_b on scale "D." Corresponding values of D_R and a_b are then found opposite each other on scales "D" and "a," respectively. For positive transparencies, where it is assumed that $D_b = \infty$, the index on scale "a" is placed opposite ∞ on scale "D." Figure 4 shows the slide in this position. Alternatively the value 0.5 on scale "a" may be placed opposite the value 0.301, ($\log 1/0.5$), on scale "D," for ideal positive transparencies.

DISCUSSION

Both Fig. 2 and Fig. 3 demonstrate the fact pointed out by Murray[1] that a change in the printed ink density produces a change in the reproduction density D_R, which varies throughout the tone range. The effect of a change in D_b is a maximum at the highest values of D_R (shadows), and a minimum at the lower values (highlights). The magnitude of this change in D_R for two values of a_b is shown in Table I. If the density difference just distinguishable by the human eye under a given set of conditions is assumed to be 0.01 at all density values, it is thus seen that a change of twenty tones in the solid black causes a change of only seven tones for a 0.9 dot ($a_b = 0.9$), and only one tone for a half-dot ($a_b = 0.5$). This phenomenon is, of course, caused by the logarithmic function of density,

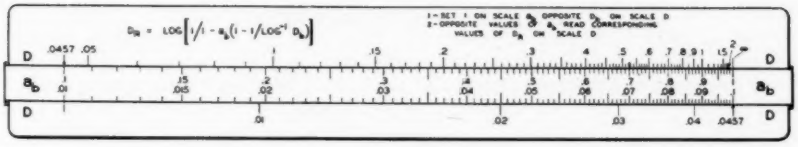

FIG. 4. Slide rule for halftone density values *versus* dot areas. a_b = fractional black dot area; D_b = optical density of black area; D_R = integrated density of region in halftone reproduction.

which is the same as the response of the human eye to brightness.

It is also apparent from Figs. 2 and 3 that a given increment in dot area produces a much larger density change in the shadows than in the highlights. For equal density increments, therefore, the increment in dot area must be considerably greater in the highlights than in the shadows.

TABLE I.

a_b	D_R, for $D_b=1.4$	D_R, for $D_b=1.2$	ΔD_R
1	1.40	1.20	0.20
0.9	0.87	0.80	0.07
0.5	0.285	0.274	0.01
0	0	0	0

The tolerance in dot area for a given tolerance in reproduction density is also much greater in the highlights than in the shadows.

It may be somewhat surprising that a half-dot ($a_b=0.5$) should produce a visual tone not halfway between white and black, but only about one-fifth of the way from white (when $D_b=1.4$). However, actual density measurements in half-dot regions on halftone prints show that the density is always just slightly less than 0.30, as calculated.

By using the chart in Fig. 2 or the slide rule in Fig. 4, the dot areas required to obtain all tone values desired in a halftone print may be determined, when the printed ink density D_b is known. A knowledge of such a series of values of dot areas would have only slight practical value, however, since they cannot be measured directly with great precision. For control of actual halftone reproduction, dot areas may be neglected and density measurements used throughout, as will be explained in a later paper. Visual inspection has definite value, however, in roughly estimating dot areas, and in judging the density and desirability of dots on halftone negatives and positives, as well as on the printed impressions.

Letter to the Editor

IN a Letter to the Editor,[1] Mr. Benford states that the textbooks are silent concerning a certain rule of geometric optics discussed by him. In view of the importance of this subject, it might be worth while to call attention to the classic work of "Czapski-Eppenstein," for example, where this matter is dealt with at length on pages 169 to 196 (third edition, 1924). Boegehold, the author of the chapter in question, also proves the applicability of the rule to imaged point sources, according to the Fermat-Clausius law given in the same book on page 226. The psychophysiological problems of subjective brightness are also discussed at some length; these are of particular importance to the physicist who is sometimes perhaps too willing to restrict his work to abstract mathematical reasoning even in instances where psychophysiological considerations might be of great practical importance.

RUDOLF AMANN,
Dartmouth Eye Institute, Dartmouth Medical School, Hanover, New Hampshire

[1] F. Benford, J. Opt. Soc. Am. **33**, 245 (1943).

An Illuminagraphic Camera

FRANK BENFORD
Research Laboratory, General Electric Company, Schenectady, New York
(Received April 22, 1943)

WHEN the sources of the illumination in a room are extended in area, that is, too large to be considered as points, the computation of illumination is apt to be both a long and a complicated process. In fact, the practical difficulties are so great that it is only rarely a mathematical study is made of the spatial characteristics of illumination from windows or other extended sources. The newer forms of illuminants are decidedly "extended" in nature, and thus we face the possibility that much of the future work in illumination design and analysis will be done either on the basis of extended source theory or on the basis of simplifications that may be erroneous to a dangerous degree.

The new type of camera to be described is an instrument to provide the architect and illuminating engineer with an engineering diagram of illuminants and windows that is theoretically correct. Photographs taken by the instrument show the illuminants and windows in a size proportional to their illuminating effect, leaving only a small fraction of the mathematics to be done to complete the analysis. It is essentially a tool for working with completed rooms, but if scale models are made it may be used as a design tool.

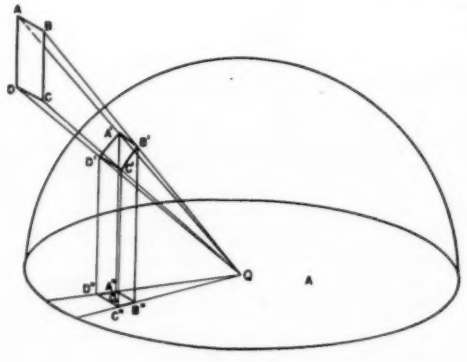

FIG. 1. The illumination at the point Q in the base plane coming from the illuminant $ABCD$ is proportional to the area $A''B''C''D''$ found by projecting the outline of the illuminant onto the hemisphere and then onto the base plane.

It has been shown[1] that the illumination from a window facing a sky of known brightness may be computed by means that are not too difficult. In Fig. 1 the illumination from the window $ABCD$ received on the horizontal plane at Q is to be computed. If a hemisphere having Q as its center is placed on the horizontal plane, a projection of the window toward the point Q will cut out a figure $A'B'C'D'$ on the surface of the hemisphere. If this figure in turn is projected onto the horizontal plane the plane figure $A''B''C''D''$ results. Let a be the area of this plane figure and A be the area of the base of the hemisphere. Then, if the sky brightness is B foot-lamberts, we have the simple expression:

$$E_H = \frac{a}{A} B \text{ footcandles} \qquad (1)$$

for the horizontal illumination at Q.

This solution is general in nature. The illuminant may have any form or outline, as seen from Q, or any position in space. Also, the actual size assigned to the hemisphere is immaterial since the same scale factor applies to both numerator and denominator of Eq. (1) and cancels out.

The illuminographic (=illuminant picture) camera utilizes the principle just outlined, giving a photograph in double projection, and the plane area of the lamp or window divided by the total area of the photograph gives a ratio that converts surface brightness of source into illumination at the selected point. The illuminated surface may be horizontal or vertical, or it may be sloping, such as the face of a drawing board. In each case the axis of the camera is placed normal to the surface to be explored.

In Fig. 2 two points, A and B, are projected radially onto a hemisphere and then to A'' and

[1] Benford, J. Opt. Soc. Am. **30**, 33 (1940).

B'' in the plane receiving illumination from the region in which A and B are located. If L is a camera lens and F is the film on which an image

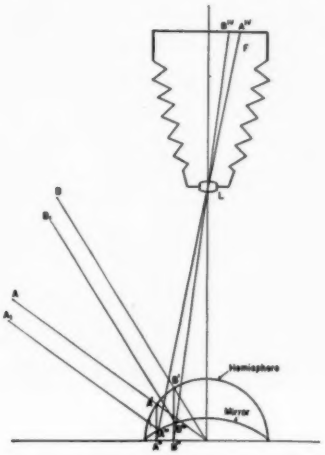

FIG. 2. This sketch shows an arrangement of camera and a special mirror so formed that images in the mirror are seen in the desired double projection as described in the text.

of A and B is desired, it will be found that the surface of the hemisphere will not serve as a mirror to direct the rays into the camera. The reflecting surface, as actually constructed, turns out to be much flatter than the hemisphere and having increasing curvature near the edge. The point A is seen as lying at A_1. There is an error here due to the separation of the lines AA' and A_1A_1''', but, since the mirror is small and the room large, this error is insignificant and may be ignored. When the mirror is correctly formed, the images of A and B will be in the desired double projection, and the light source that they help outline will appear in a size that is directly proportional to its illuminating value.

The mirror was designed by selecting points $AB\cdots$ at various angles above the horizontal plane and then computing the positions $A''B''\cdots$ of the double projection. Given the focal length L of the lens and the approximate size of the photograph the tangents (but not the positions) of the mirror surfaces at A''' and B''' were computed. A large scale section drawing was made by fitting these tangents together to form a smooth curve. A templet made to this curve served as a guide for rough grinding the mirror, but from then on the tests were optical.

A working model of the illuminagraphic camera is shown at the bottom of Fig. 3. The line of lamps up the pilaster on the right are at angles of 0°, 15°$\cdots$75° above the horizontal, and the two at the left are at 0° and 15°. The images of these lamps were observed on a calibrated frosted film in the position of the photographic film, and the figure of the mirror was altered until a satisfactory fit was obtained. Figure 4 shows the final spacing. The calibration lines were copied on the exposed film and each image should fall on a line, except one extra image near 68° for which there is no calibration line.

The mirrors and camera were mounted in a fixed relation on a chemical ring stand, as illustrated in Fig. 5, where the illumination on the surface of a desk is being investigated. The illuminagraph, Fig. 6, for this point in the room shows the single window to occupy about 3 percent of the area of the complete photograph. A photometric comparison of the sky brightness with the illumination on the desk gave the same ratio and, hence, the photograph can be used

FIG. 3. The illuminagraphic camera is here shown standing between two vertical lines of lamps that served as test objects for testing and correcting the figure of the mirror that is the vital part of the instrument.

to predict illumination under different sky conditions.

This type of photograph gives a complete view of the ceiling and all parts of the walls above the level of the mirror, and everything is pictured in the double projection of Fig. 1. The camera itself occupies an unduly prominent position in the center of the picture, and obviously a smaller type of camera would be an improvement. The square supporting rod always appears in a radial position. If the reader will observe only the segment of picture nearest him and slowly rotate the photograph he will get the same effect he would get by standing where the camera was

FIG. 4. This photograph illustrates the method of testing the mirror. The images of the lamp filaments should lie on the (extended) calibration lines when the mirror is correctly formed and is in the proper position in relation to the camera.

placed and then turning around to face various parts of the room.

The illumination received from a window may be influenced by the presence of external objects such as a tree or a building. Figure 7 shows such a situation and planimeter readings show the window to occupy 9.98 percent of the area, and the external buildings block out 2.59 percent, leaving the windows to furnish an illumination of 7.37 percent of the sky brightness. This particular situation would entail almost unsurmountable difficulties if a strict solution by equations were attempted.

There are other common problems, such as finding the illumination on a sloping drawing

FIG. 5. The camera is here placed on a desk whose illumination is under investigation, and the image in the mirror seen on the base of the ring stand includes all parts of the room above the level of the mirror.

board, that involve considerable preliminary work to set up the equations, and these equations are long, since solutions for three mutually perpendicular planes must first be found, then multiplied by the direction cosines of the board,

FIG. 6. This illuminagraph shows the window, wall, and ceiling in sizes that are strictly proportional to their effectiveness in directing light to the desk shown in the preceding figure.

FIG. 7. This photograph was taken to show how external obstructions may influence the light received from a window. Here planimeter measurements show the illumination to be reduced by about one quarter by the buildings seen through the lower part of the window.

and these products then added vectorially. In Fig. 8 this problem is solved photographically for a board some 11 feet from the window, and in Fig. 9 the solution is repeated for a position 3 feet from the window. The illuminations are in the same ratio as the areas of the images in the photographs, and certain details of importance are revealed by a comparative study of the two photographs.

In Fig. 9 the sides of the window are formed by the brick wall and not by the sash, and the top is framed by the lintel. The window opening here has grown some four inches in width and height as the camera is moved closer and at the same time the effective windows opening has moved eight inches beyond the glass. Any precision that might be put into a mathematical computation of the illumination from this window would be nullified by the change in size, shape and location of the effective window, but these things are automatically taken care of by the illuminagraph.

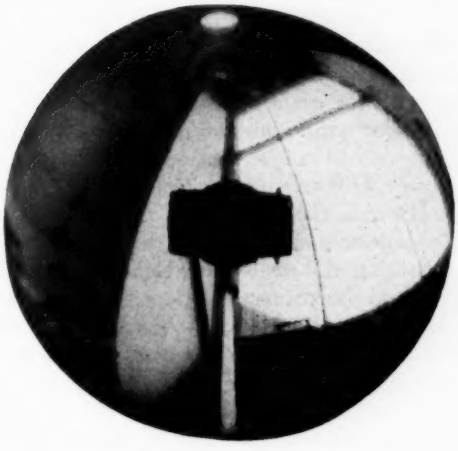

FIG. 9. The drawing board is here within 3 feet of the window and the relative sizes of the individual panes of glass are measures of their contributions to the illumination of the board.

FIG. 8. This illuminagraph was taken with the instrument set against the face of a drawing board tilted at about 45° and turned at an angle with the window so as to secure the best illumination at a point some eleven feet away.

One important feature is brought out by comparing the sizes of the panes of glass as projected to the two positions. At the 11-foot position the upper and lower sash are about equally effective as illuminants, but at the 3-foot position the lower sash predominates and the central pane of glass is noticeably larger than the two side panes. It is in the analysis of just such details as these that the photographic method may have its greatest value.

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The Specification of Foveal Adaptation

PARRY MOON, *Massachusetts Institute of Technology, Cambridge, Massachusetts*

AND

DOMINA EBERLE SPENCER, *The American University, Washington, D. C.*

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1. INTRODUCTION

THE phenomena associated with the adjustment of the retina to the quantity and quality of the light are familiar to everyone. Such adjustment is called *adaptation*. Various names, such as "induction," "color fatigue," "glare," are applied to specific phenomena, which, however, are believed to have a common basis in retinal adaptation. There is evidence that adaptation is a photochemical process.[1] In the present paper, however, the photochemical hypothesis will not be necessary and the treatment will be based on experiment rather than on photochemical theory.

The question arises as to the best way of specifying the state of adaptation of a given portion of the retina. Consider first the case where all radiant energy under consideration has the same relative spectral distribution. Such a condition often occurs in practice, as in highway lighting with incandescent lamps. The state of adaptation of a given portion of the retina at a given instant is then conveniently specified by the *adaptation helios* H_A described below.

If the eye is exposed for a sufficient time to a helios H, which is uniform over the entire visual field, every part of the retina will reach an equilibrium condition corresponding to this helios.[2] Then the eye will be said to be adapted to the level $H_A = H$.

Ordinarily the visual field is not of uniform helios, and consequently the state of adaptation is different for different parts of the retina. Adaptation is also a function of time: It is both temporal and spacial. For any given localized area at a specific instant, however, the assumption will be made that the instantaneous state of adaptation can be specified by the equivalent H_A of a uniform source that fills the whole visual field for sufficient time so that equilibrium is obtained.[3] The criterion for equivalence of adaptation is found by employing any one of a number of visual tests, such as contrast sensitivity or critical flicker frequency. There is considerable experimental evidence[3] that the various criteria lead to the same values of adaptation helios H_A. Evidently the same state of adaptation of a given portion of the retina can be produced by infinitely many helios distributions in the visual field.

Though the adaptation of any part of the retina may be considered, the adaptation of the fovea is of prime importance and it only will be treated in this paper. For the special case of uniform color quality over the entire visual field, the instantaneous state of foveal adaptation may be specified by a *single number*, such as H_A, and this quantity will depend on the present and past excitation of the entire retina. If variations in color quality are present, the one-number specification becomes inadequate and must be replaced by a 3-number designation in accordance with the trichromatic theory. Thus the instantaneous state of foveal adaptation is specified by a *vector function of time:*

$$\mathbf{V}_A(t) = [X_A(t),\ Y_A(t),\ Z_A(t)],$$

where the coordinates $X_A(t)$, $Y_A(t)$, $Z_A(t)$ are scalar functions which depend on the present and past excitation of the whole retina.

The basic idea, that a non-uniform helios distribution can be replaced by an equivalent uniform distribution, was originated by Holladay in his noteworthy researches on glare.[4] The concept has been extended by Stiles and his collaborators,[3] whose "equivalent background

[1] S. Hecht, J. Opt. Soc. Am. **32**, 40 (1942).
[2] Parry Moon, J. Opt. Soc. Am. **32**, 348 (1942).
[3] W. S. Stiles and B. H. Crawford, *Discussion on Vision* (Cambridge University Press, London, 1932), p. 194; W. S. Stiles, Proc. Roy. Soc. London **104B**, 322 (1929).
[4] L. L. Holladay, J. Opt. Soc. Am. **12**, 271 (1926); **14**, 1 (1927).

brightness β" is essentially the same as our adaptation helios H_A. The development of the *composite stimulus*[5] allowed the further extension of the adaptation concept, and this extension to a 3-number specification was originated by one of the authors and was presented in a previous paper.[6] The present paper is an amplification of the former work.

2. POSTULATES

The fundamental assumption that must be made in all visual theory is that a complicated organism will give reproducible results which can be approximated by mathematical expressions. To anyone who has noted the erratic fluctuations obtained from day to day in visual tests, this basic assumption is disquieting. But it must be made if anything is to be accomplished in visual theory. It seems advisable also to establish a set of postulates on which the following theory can be based. These postulates appear to be in accord with the available experimental data, though of course further research may show the need for their revision.

1. The visual field will be divided into two parts:

(a) The central part of the field, which is imaged on the fovea. This part will be taken as a circular disk subtending a visual angle of 1.5°.

(b) The surround, consisting of all the visual field outside a 1.5° circular disk. Postulate 1 is a frank simplification of the problem, for it is well known that the fovea is not exactly circular and has no definite boundary.

2. There is no spacial variation of adaptation over the fovea. The fovea will be considered as a unit whose instantaneous adaptation can be designated by a number or set of three numbers.

3. The effect of a concentrated light source is given by Eq. (2).

4. The system is linear; that is, the effects of individual sources are additive, in agreement with the experimental work of Crawford[7] and others.

5. The C.I.E. trichromatic data apply to foveal adaptation.

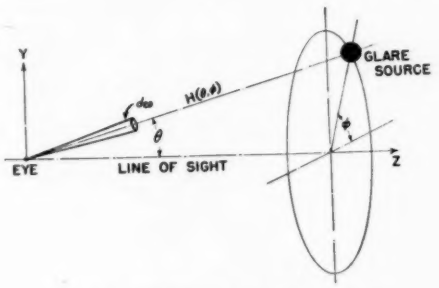

FIG. 1. Glare source in the field of view.

6. The experimental constants that were obtained with incandescent glare sources apply without change to chromatic light.[8]

3. ADAPTATION FOR LIGHT FROM INCANDESCENT LAMPS

According to the extensive research of Holladay,[4] a uniform visual field of brightness B containing a single glare source can be replaced (as regards foveal adaptation) by a completely uniform field of brightness β, where

$$\beta = B + (kD_G/\theta^n). \tag{1}$$

D_G is the luminous flux density, produced by the glare source, on a plane which is at the eye and which is perpendicular to the line of sight. The angle θ is between the glare source and the line of sight.

The experimental results of Holladay were fitted in a satisfactory manner with $n=2$. Stiles and Crawford, however, in their careful investigation of the subject obtained a better fit with $n=1.5$. This low value was caused by the rather large size of their glare source; and when corrections were applied, their value of n became more nearly that of Holladay who used a very small glare source. Thus in the most recent work (Stiles and Dunbar)[9] the conclusion is reached that, on the basis of new experimental results and a reconsideration of the old, the value of n

[5] D. E. Spencer, J. Opt. Soc. Am. **33**, 10 (1943).
[6] D. E. Spencer, "Adaptation in color space," presented at Summer Meeting of O.S.A., Cambridge, Massachusetts, July 22, 1942.
[7] B. H. Crawford, Proc. Phys. Soc. **48**, 35 (1936).
[8] Pub. Dept. Sci. Ind. Res., Illum. Res. Tech. Pap. No. 20, 1937; W. Arndt, Das Licht **3**, 213 (1933).
[9] W. S. Stiles and C. Dunbar, Illum. Res. Comm. (Great Britain) Tech. Pap. No. 16, 1935.

should be 2. Also, $k=10$ if β and B are in candles per unit area, D_G in lumens per unit area, and θ in degrees.

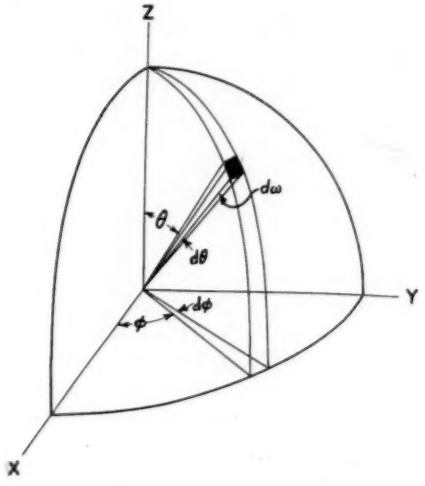

FIG. 2. Spherical coordinate system used in the calculation of the glare effect.

Accepting the Stiles and Dunbar conclusions, therefore, and changing the units to agree with our other work, we obtain for the effect of a single glare source against a dark background,

$$H_A=KD_G/\theta^2, \tag{2}$$

where H_A = adaptation helios; that is, the value of H (blondels) of a completely uniform field which will result in the same contrast sensitivity as that produced by the glare source alone,
D_G = glare flux density at the eye (lumens/m^2),
$K=9.6\times10^{-3}$,
θ = angle between line of sight and glare source, in radians.

Given a glare source subtending a solid angle $d\omega$ at the eye (Fig. 1). The helios in the given direction is $H(\theta, \phi)$. Then

$$dD_G=[H(\theta, \phi)/\pi]\cos\theta\, d\omega.$$

If spherical coordinates are used and the glare source subtends the angles $d\theta$ and $d\phi$ (Fig. 2),

$$d\omega=(d\phi\sin\theta)d\theta$$

and

$$dD_G=[H(\theta, \phi)/\pi]\sin\theta\cos\theta\, d\theta\, d\phi. \tag{3}$$

Thus, for a source subtending a small visual angle, the adapting helios is

$$dH_A=[KH(\theta, \phi)/\pi\theta^2]\sin\theta\cos\theta\, d\theta\, d\phi.$$

With a large source, according to Postulate 4,

$$H_A=\frac{K}{\pi}\int_{\Phi_1}^{\Phi_2}d\phi\int_{\Theta_1}^{\Theta_2}\frac{H(\theta, \phi)}{\theta^2}\sin\theta\cos\theta\, d\theta. \tag{4}$$

Equation (4) is the basic equation for calculating the foveal adaptation helios for any helios distribution in the field of view. In general Θ_1 and Θ_2 will be functions of ϕ, and H will be a function of both θ and ϕ.

For the special case of a uniform circular field with $H=$const., $\Theta_1=$const., $\Theta_2=$const., $\Phi_1=0$, $\Phi_2=2\pi$, Eq. (4) reduces to

$$H_A=2KH\int_{\Theta_1}^{\Theta_2}\frac{\sin\theta\cos\theta\, d\theta}{\theta^2}. \tag{5}$$

But

$$\sin\theta\cos\theta=\tfrac{1}{2}\sin 2\theta,$$

so

$$H_A=2KH\int_{2\Theta_1}^{2\Theta_2}\frac{\sin x\, dx}{x^2}.$$

Let $u=\sin x$, $dv=dx/x^2$. Then integration by parts gives

$$\int\frac{\sin x\, dx}{x^2}=-\frac{\sin x}{x}+\int\frac{\cos x\, dx}{x}$$

and

$$H_A=2KH\left[\frac{\sin 2\Theta_1}{2\Theta_1}-\frac{\sin 2\Theta_2}{2\Theta_2}-\int_{\infty}^{2\Theta_1}\frac{\cos x\, dx}{x}+\int_{\infty}^{2\Theta_2}\frac{\cos x\, dx}{x}\right]. \tag{6}$$

This equation applies to any ring-shaped field, with the radii of the ring subtending the visual angles Θ_1 and Θ_2.

The equation is now applied to the effect of a luminous surround with $\Theta_1=0.0131$ radian (1.5° diameter). The first term of Eq. (6) now becomes essentially unity, and

$$H_A/H=2K\left[1-\frac{\sin 2\Theta_2}{2\Theta_2}-Ci(2\Theta_1)+Ci(2\Theta_2)\right], \tag{6a}$$

where $Ci(x)$ is the *cosine integral*. A good table of this function is now available,[10] and less complete tables have been published in a number of places.[11]

The outer boundary of the visual field is not circular in shape but subtends an angle of approximately 45° upward and 90° sideways. The effect on foveal adaptation of these extreme parts of the retina, however, is ordinarily very small so the replacement of the true visual field by a circular one is permissible. Table I shows the effect of changing Θ_2 through the widest possible range that could occur with an unlimited uniform source. The fourth column gives H_A/H for surround, calculated from Eq. (6). But if the entire field of view is of helios H, the eye adapts itself to this helios and $H_A/H=1.00$. Thus the effect of foveal illumination in determining foveal adaptation is given by the last column of the table. The noteworthy feature of Table I is that a change of Θ_2 within the physiologically prescribed limits has almost no effect, the total variation in the effect of the surround being only 2 percent when Θ_2 changes from 1.0 to 1.57. It is convenient to take Θ_2 as 1.0 radian (57.3°).

Similarly, the effect of changing Θ_1 is easily investigated. Histological evidence proves that $2\Theta_1$ must certainly lie between 1° and 2°; and this total variation does not make an important change in the relative contributions of surround and fovea. One must conclude, therefore, that

TABLE I. Effect of the size of surround. $\Theta_1=0.0131$, $Ci(2\Theta_1)=-3.0650$.

Θ_2	$\frac{\sin 2\Theta_2}{2\Theta_2}$	$Ci(2\Theta_2)$	Contribution of surround (H_A/H)	Contribution of fovea $(1-H_A/H)$
$\pi/4$	0.636	0.472	0.0749	0.9251
1.0	0.455	0.423	0.0774	0.9226
1.1	0.368	0.375	0.0781	0.9219
1.2	0.281	0.317	0.0787	0.9213
1.3	0.199	0.253	0.0791	0.9209
1.4	0.120	0.187	0.0792	0.9208
1.5	0.047	0.120	0.0794	0.9206
$\pi/2$	0.000	0.074	0.0795	0.9205

[10] *Tables of Sine, Cosine, and Exponential Integrals* (Nat. Bur. Stand., Washington, D. C., 1940).

[11] E. Jahnke and F. Emde, *Funktionentafeln* (Teubner, Leipzig, 1938); British Assn. Adv. Sci., *Mathematical Tables* (Cambridge University Press, London, 1931), Vol. I.

foveal adaptation produced by a completely uniform field is caused largely by the portion of the field that is imaged on the fovea, the entire surround

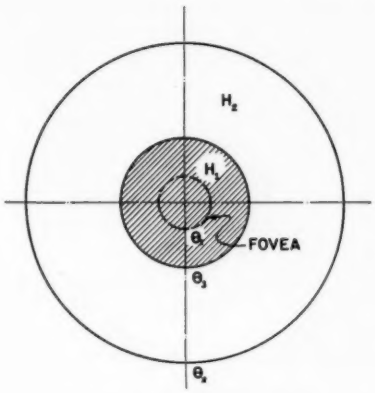

FIG. 3. A two-part visual field.

contributing less than 10 percent of the total effect. This result does not seem to have been stated before, perhaps because the equations were not integrated previously.

4. APPLICATIONS

The preceding section has shown that reasonable values are $\Theta_1=0.0131$, $\Theta_2=1.00$ for an unlimited uniform source. Under these circumstances, the direct illumination of the fovea contributes 0.923 of the total foveal adaptation. These results can now be applied to the general case of steady-state foveal adaptation. If the helios of a circular disk imaged on the fovea is H_B, and the helios of the surround has an arbitrary distribution $H(\theta,\phi)$, the resulting foveal adaptation is

$$H_A=0.923H_B+\frac{K}{\pi}\int_{\Phi_1}^{\Phi_2}d\phi \times\int_{\Theta_1}^{\Theta_2}\frac{H(\theta,\phi)}{\theta^2}\sin\theta\cos\theta\,d\theta. \quad (7)$$

If the field has axial symmetry, Eq. (7) reduces to

$$H_A=0.923H_B+0.0192\int_{\Theta_1}^{\Theta_2}\frac{H(\theta)}{\theta^2}\sin\theta\cos\theta\,d\theta. \quad (8)$$

Consider a central circular field of helios H_1 surrounded by a field of helios H_2 (Fig. 3). The radius of the inner field subtends a visual angle of Θ_3. Such a configuration is used in various pieces of optical apparatus and in visual tests.

From Eq. (8), for the usual case of a central spot that covers more than the fovea ($\Theta_3 \geqq \Theta_1$),

$$H_A = 0.923H_1 + 0.0192\Big\{H_1[1 - Ci(2\Theta_1)] - H_2\Big[\frac{\sin 2\Theta_2}{2\Theta_2} - Ci(2\Theta_2)\Big] - (H_1 - H_2)\Big[\frac{\sin 2\Theta_3}{2\Theta_3} - Ci(2\Theta_3)\Big]\Big\}. \quad (9)$$

For a small central spot ($\Theta_3 \leqq \Theta_1$),

$$H_A = 0.923\Big[\frac{H_1\Theta_3^2 + H_2(\Theta_1^2 - \Theta_3^2)}{\Theta_1^2}\Big] + 0.0192H_2\Big[1 - \frac{\sin 2\Theta_2}{2\Theta_2} - Ci(2\Theta_1) + Ci(2\Theta_2)\Big]. \quad (10)$$

A convenient representation is obtained by expressing H_2 in terms of H_1:

$$H_2 = kH_1. \quad (11)$$

Then Eq. (9) becomes

$$H_A/H_1 = 0.923 + 0.0192\Big[(1 - Ci(2\Theta_1)) - k\Big(\frac{\sin 2\Theta_2}{2\Theta_2} - Ci(2\Theta_2)\Big)\Big] - 0.0192(1-k)\Big[\frac{\sin 2\Theta_3}{2\Theta_3} - Ci(2\Theta_3)\Big] \quad (9a)$$

and when the recommended values, $\Theta_1 = 0.0131$, $\Theta_2 = 1.00$, are used,

$$H_A/H_1 = [1.0006 - 0.0006k] - 0.0192(1-k)\Big[\frac{\sin 2\Theta_3}{2\Theta_3} - Ci(2\Theta_3)\Big]. \quad (9b)$$

If $k = 0$, for example,

$$H_A/H_1 = 1.0006 - 0.0192Q;$$

$k = 0.1$,

$$H_A/H_1 = 1.0005 - 0.0173Q;$$

$k = 0.5$,

$$H_A/H_1 = 1.0003 - 0.0096Q;$$

$k = 1.0$,

$$H_A/H_1 = 1.0000;$$

$k = 1.5$,

$$H_A/H_1 = 0.9997 + 0.0096Q;$$

$k = 2.0$,

$$H_A/H_1 = 0.9994 + 0.0192Q;$$

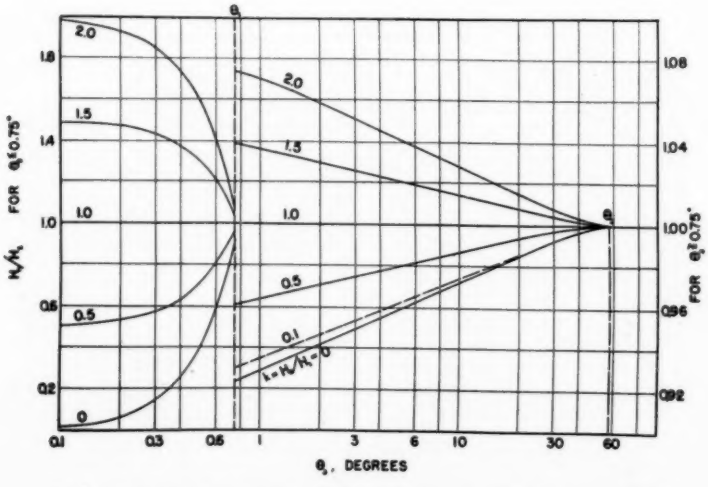

FIG. 4. Effect of changing the helios of the outer part of the visual field.

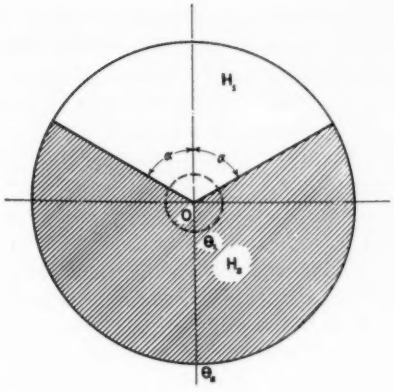

FIG. 5.

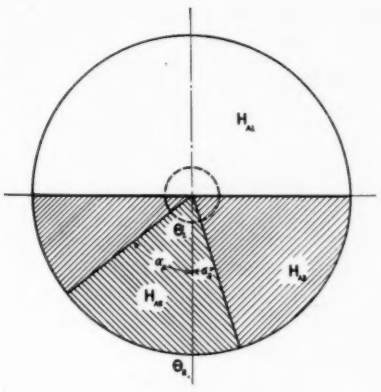

FIG. 6.

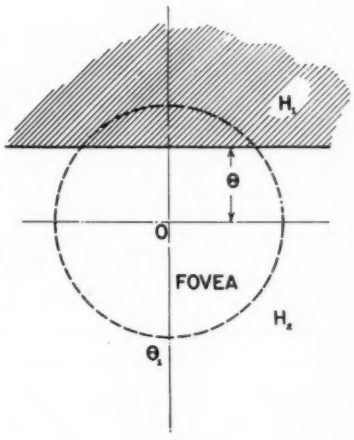

FIG. 7.

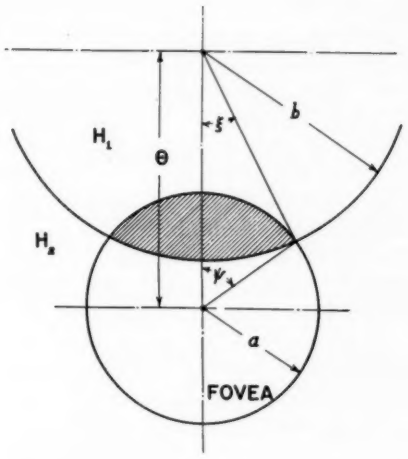

FIG. 8.

FIGS. 5–8. Examples of visual fields.

where

$$Q=\frac{\sin 2\Theta_3}{2\Theta_3}-Ci(2\Theta_3).$$

The effect of changing the size and helios of the outer part of the field is shown in Fig. 4, as calculated by use of the foregoing equations.

H_A/H_1 is plotted against Θ_3 and gives a clear picture of what happens in optical apparatus when the central, luminous part of the visual field is increased in size. If the outer part has zero helios, $k=0$. The lowest curve then shows that the adaptation helios increases from $0.923H_1$, where all the extrafoveal field is dark, to $1.00H_1$ where the entire visual field is luminous. Ninety-nine percent of complete adaptation, for instance, is obtained when the radius of the luminous part of the field subtends a visual angle of 28°; 98 percent is obtained when the luminous part subtends 17°. Curves are also shown for $k=0.1$, 0.5, 1.0, 1.5, and 2.0. When Θ_3 is less than the foveal angle (0.75°), the curves run through a larger range of adaptation helios and it is necessary in Fig. 4 to employ a different scale for this part of the graph.

If $\Theta_3 \leqq \Theta_1$, Eq. (10) gives

$$H_A/H_1 = 0.923\left[\frac{k\Theta_1^2+(1-k)\Theta_3^2}{\Theta_1^2}\right] + 0.0192k\left[1-\frac{\sin 2\Theta_2}{2\Theta_2} - Ci(2\Theta_1)+Ci(2\Theta_2)\right], \quad (10a)$$

or

$$H_A/H_1 = k+5380(1-k)\Theta_3^2. \quad (10b)$$

If $k=0$, for instance,

$$H_A/H_1 = 5380\Theta_3^2;$$

$k=0.5$,

$$H_A/H_1 = 0.500+2690\Theta_3^2;$$

$k=1.0$,

$$H_A/H_1 = 1.000;$$

$k=1.5$,

$$H_A/H_1 = 1.500-2690\Theta_3^2;$$

$k=2.0$,

$$H_A/H_1 = 2.000-5380\Theta_3^2.$$

Calculated values for central fields smaller than the fovea are also shown in Fig. 4.

Continuous radial variations in helios are handled by use of Eq. (8). For example, if $H(\theta)=H_s\cdot\theta$, the integral becomes

$$H_s\int_{\Theta_1}^{\Theta_2}\frac{\sin\theta\cos\theta\,d\theta}{\theta} = \frac{H_s}{2}\int_{2\Theta_1}^{2\Theta_2}\frac{\sin x\,dx}{x} = \frac{H_s}{2}[Si(2\Theta_1)-Si(2\Theta_2)]$$

and

$$H_A = 0.923H_B+0.0096H_s \times[Si(2\Theta_1)-Si(2\Theta_2)]. \quad (12)$$

The field can also be divided into sections separated by radial lines without introducing much additional complexity. Consider the two-part field of Fig. 5. One section has such a helios distribution $H(\theta)$ that if it were continuous through 360° about 0 it would give an adaptation helios H_{A1}. The other section would produce an adaptation level H_{A2}. With the angular distribution shown in Fig. 5, the adaptation helios is

$$H_A = \frac{1}{\pi}[H_{A1}\alpha+H_{A2}(\pi-\alpha)]. \quad (13)$$

Equation (13) is applicable to helios distributions that are functions of θ or are constants. For example, let Fig. 5 represent a sky of helios H_1 in a mountain valley with $\alpha=\pi/3$ radian and with mountains of helios H_2. If the observer is looking fixedly at point 0, his foveal adaptation is specified by

$$H_A = H_1/3+2H_2/3.$$

An obvious extension can be made to a larger number of sections. For example, a sky (Fig. 6) would produce an adaptation of H_{A1} if the sky were continued through 2π radians. A river or a road with angles α_2 and α_3 would produce the adaptation level H_{A2}, while a third part of the landscape would give H_{A3}. Then, obviously, the resulting adaptation level is

$$H_A = H_{A1}/2+H_{A2}\frac{(\alpha_2+\alpha_3)}{2\pi}+H_{A3}\frac{(\pi-\alpha_2-\alpha_3)}{2\pi}. \quad (14)$$

More complicated configurations, where H varies with both θ and ϕ, are treated by means of Eq. (7). Ordinarily the integrations must be performed mechanically rather than analytically. But often the effect of the surround is small so that a fairly good approximation is obtained by considering that foveal adaptation depends on the fovea only. Consider, for example, the adaptation produced by sea of helios H_2 and sky of helios H_1, where the horizon makes an angle Θ with the line of sight (Fig. 7). By simple geometry, and neglecting the effect of the surround, one obtains the adaptation helios

$$H_A = H_2+\frac{(H_1-H_2)}{\pi}[\cos^{-1}\Theta-\Theta(1-\Theta^2)^{\frac{1}{2}}]. \quad (15)$$

Similarly, for a circular field which is eccentric with respect to the line of sight (Fig. 8), the adaptation helios is

$$H_A = H_2+\frac{(H_1-H_2)}{\pi a^2}\{a^2[\psi-\sin\psi\cos\psi] + b^2[\xi-\sin\xi\cos\xi]\}. \quad (16)$$

5. COLOR ADAPTATION

Equation (7) gives a one-number specification of the state of adaptation of the fovea. The

constants were obtained by measurements made with light from incandescent lamps. The helios can be calculated from the spectral distribution curve by use of the equation,

$$H(\theta, \phi) = \int_0^\infty v(\lambda; \theta, \phi) \cdot H_\lambda(\theta, \phi) d\lambda, \quad (17)$$

where $v(\lambda; \theta, \phi)$ is the lamprosity function for the human eye, and $H_\lambda(\theta, \phi)$ represents the ordinate (watt m^{-2} $micron^{-1}$) of the spectral distribution curve. Here the lamprosity function is supposed to be obtained by use of a small source of homogeneous radiation placed at the angles θ and ϕ from the line of sight. For positions within the fovea, the function $v(\lambda; \theta, \phi)$ is independent of θ and ϕ and is represented by the curve for pure cone vision, having its peak at approximately 0.565μ. For positions in the peripheral region, the function may depend to some extent on the relative cone and rod densities at the part of the retina under consideration.

In a manner exactly similar to that used in the trichromatic specification of light, one can specify the state of color adaptation of the fovea. Such an extension of the usual concept of adaptation seems to have been made first by one of the authors.[6] It is a 3-number specification, which can be written, in analogy with the equations of the previous section,

$$\left.\begin{aligned} X_A &= k_1 X_B + \frac{K_1}{\pi} \int d\phi \int \frac{X(\theta, \phi)}{\theta^{f_1}} \sin\theta \cos\theta \, d\theta, \\ Y_A &= k_2 Y_B + \frac{K_2}{\pi} \int d\phi \int \frac{Y(\theta, \phi)}{\theta^{f_2}} \sin\theta \cos\theta \, d\theta, \\ Z_A &= k_3 Z_B + \frac{K_3}{\pi} \int d\phi \int \frac{Z(\theta, \phi)}{\theta^{f_3}} \sin\theta \cos\theta \, d\theta. \end{aligned}\right\} \quad (18)$$

Here X_B, Y_B, Z_B are the C.I.E. coordinates of the radiation falling directly on the fovea, while $X(\theta, \phi)$, $Y(\theta, \phi)$, $Z(\theta, \phi)$ refer to the surround:

$$\left.\begin{aligned} X(\theta, \phi) &= \int_0^\infty \bar{x}(\lambda; \theta, \phi) \cdot H_\lambda(\theta, \phi) d\lambda, \\ Y(\theta, \phi) &= \int_0^\infty \bar{y}(\lambda; \theta, \phi) \cdot H_\lambda(\theta, \phi) d\lambda, \\ Z(\theta, \phi) &= \int_0^\infty \bar{z}(\lambda; \theta, \phi) \cdot H_\lambda(\theta, \phi) d\lambda. \end{aligned}\right\} \quad (19)$$

Evidently the three functions of Eq. (19) replace the single function $H(\theta, \phi)$ of Eq. (17). The complete color adaptation of the fovea is specified by the number-triple (X_A, Y_A, Z_A).

Two hypotheses have been advanced to explain the known effect of extrafoveal illumination on the state of foveal adaptation. The two hypothetical causes are

(1) Scattering of light in the eye. Some of the scattered light falls on the fovea and thus alters its adaptation level.

(2) Action of transverse neurons in the retina. Excitation of parafoveal receptors results in the propagation of impulses along the transverse neurons to the fovea, and these impulses alter in some way the foveal adaptation.

Evidently the two hypotheses will give different predictions with respect to the functions $v(\lambda; \theta, \phi)$, $\bar{x}(\lambda; \theta, \phi)$, $\bar{y}(\lambda; \theta, \phi)$, $\bar{z}(\lambda; \theta, \phi)$. All the receptors of the fovea are cones, and by the first hypothesis only the spectral response of the fovea is considered in foveal adaptation. Thus (assuming non-selective scattering) the spectral response curves must be independent of θ and ϕ; and $v(\lambda)$, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ will be the functions applying to pure cone vision.

Under hypothesis (2), on the other hand, these functions apply to cone vision in the fovea, while they reduce to the one-number specification of rod vision at sufficiently large values of θ. For intermediate values of θ, the mathematical functions must be determined by the relative cone and rod densities.

Hypothesis (1) was proposed by Holladay[4] who developed a mathematical theory of scattering. Stiles[12] also considered the subject but concluded that the theory was not in agreement with experiment. This fact, however, does not necessarily invalidate the first hypothesis, for it may mean that some of the assumptions of the theory (neglection of scattering in the sclera, for instance) are at fault. Against the second hypothesis may be stated the experimental result that a concentrated light focused on the blind spot produces a change in foveal adaptation.[13] Also, the research of Luckiesh and Holladay shows that a change in the color of a concentrated glare

[12] W. S. Stiles, Proc. Roy. Soc. London **105B**, 131 (1929).
[13] W. S. Stiles and B. H. Crawford, Proc. Roy. Soc. **122B**, 255 (1937).

source has essentially no effect on the foveal adaptation level, provided D_G remains the same.[14] The same result is shown even more conclusively by Stiles and Crawford,[14] who state, "It was found that for a given glare illumination at the eye the value of the l.b.i. is independent of the color of the glare source." Investigations of the blinding effects of automobile headlights of various colors leads to the same general result.[15] The conclusion is, therefore, that for foveal adaptation (at least until further data are available) it is unnecessary to consider the variations with θ and ϕ of spectral curves. This amounts to the tentative acceptance of the first hypothesis, which allows the use of the same constants in the three equations (18), in accordance with Postulate 6. The C.I.E. standard functions are not for pure foveal vision but their use seems advisable for simplicity, and they may well be in better agreement with the facts than would be the curves for cone vision.

Thus the previous equations will be rewritten as follows:

$$H_A=0.923H_B+\frac{9.6\times10^{-3}}{\pi}\int_{\Phi_1}^{\Phi_2}d\phi\times\int_{\Theta_1}^{\Theta_2}\frac{H(\theta,\phi)}{\theta^2}\sin\theta\cos\theta\,d\theta, \quad (20)$$

$$\left.\begin{aligned}X_A&=0.923X_B+\frac{9.6\times10^{-3}}{\pi}\int_{\Phi_1}^{\Phi_2}d\phi\times\int_{\Theta_1}^{\Theta_2}\frac{X(\theta,\phi)}{\theta^2}\sin\theta\cos\theta\,d\theta,\\ Y_A&=0.923Y_B+\frac{9.6\times10^{-3}}{\pi}\int_{\Phi_1}^{\Phi_2}d\phi\times\int_{\Theta_1}^{\Theta_2}\frac{Y(\theta,\phi)}{\theta^2}\sin\theta\cos\theta\,d\theta,\\ Z_A&=0.923Z_B+\frac{9.6\times10^{-3}}{\pi}\int_{\Phi_1}^{\Phi_2}d\phi\times\int_{\Theta_1}^{\Theta_2}\frac{Z(\theta,\phi)}{\theta^2}\sin\theta\cos\theta\,d\theta,\end{aligned}\right\} \quad (21)$$

where

$$H(\theta,\phi)=\int_0^\infty v(\lambda)\cdot H_\lambda(\theta,\phi)d\lambda, \quad (22)$$

$$\left.\begin{aligned}X(\theta,\phi)&=\int_0^\infty\bar{x}(\lambda)\cdot H_\lambda(\theta,\phi)d\lambda,\\ Y(\theta,\phi)&=\int_0^\infty\bar{y}(\lambda)\cdot H_\lambda(\theta,\phi)d\lambda,\\ Z(\theta,\phi)&=\int_0^\infty\bar{z}(\lambda)\cdot H_\lambda(\theta,\phi)d\lambda.\end{aligned}\right\} \quad (23)$$

For the complete visual field, the limits of integration are $\Phi_1=0$, $\Phi_2=2\pi$, $\Theta_1=0.0131$, $\Theta_2=1.00$. The weighting functions $v(\lambda)$, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ are the C.I.E. standards (Postulate 5) or their analytic counterparts,[16] and $v(\lambda)$ and $\bar{y}(\lambda)$ are the same except for a factor of 621. These equations allow the calculation, for the first time, of trichromatic foveal adaptation for any given visual field. The integrals can always be evaluated, either analytically or mechanically, and the results can be employed in the composite stimulus.[5]

As an example of color adaptation, consider the change of adaptation when the test-spot color moves along the spectral locus at constant helios and the outer part of the field remains constant. The angles subtended by the radii of the central field and the surrounding field are 1° and 30°, respectively, while the fovea is taken with radius $\frac{3}{4}$° as in the previous sections. The trichromatic coordinates of the surrounding field are $X=79.1$, $Y=75.0$, $Z=95.2$. The helios of the central field is twice that of the outer field, or $Y=150$ blondels.

The X and Z coordinates of the test spot will now be varied along the spectral locus keeping Y constant. By use of Eqs. (7) and (21) the following equations are obtained for the trichromatic coordinates of the adaptation vector $\mathbf{H}_A$:

$$\left.\begin{aligned}X_A&=0.928X_1+5.05,\\ Y_A&=143.8,\\ Z_A&=0.928Z_1+6.05.\end{aligned}\right\} \quad (24)$$

[14] M. Luckiesh and L. L. Holladay, J. Opt. Soc. Am. **11**, 311 (1925); W. S. Stiles and B. H. Crawford, Proc. Roy. Soc. **116B**, 98 (1934).

[15] Illum. Res. Comm. (Great Britain) Tech. Pap. No. 20, 1937.

[16] P. Moon and D. E. Spencer, J. Opt. Soc. Am. **33**, 89 (1943).

These equations were used in the computation of the dotted curve in Fig. 9. The solid curve is the spectral locus according to the analytical representation.[16] The two curves are seen to have the same general shape and to lie within a few minimum perceptible steps of each other for all wavelengths. This means that the white surrounding field has very little effect on the state of foveal adaptation and merely reduces the saturation of the adaptation color from that of the test spot in all cases.

As a second example, consider the effect of changing the surrounding field, keeping a fixed test spot. The dimensions and helios values are as before. Suppose the color quality of the surrounding field is changed along the Planckian locus and that the fixed spot is specified by the coordinates $X_1=316$, $Y_1=150$, $Z_1=64.2$. The test spot represents one of the reds (Ellipse 19)[17] used by MacAdam.[18] The trichromatic coordinates of the resulting adaptation vector are

$$\left.\begin{aligned} X_A &= 293+0.0637X_2, \\ Y_A &= 143.8, \\ Z_A &= 59.6+0.0637Z_2, \end{aligned}\right\} \qquad (25)$$

where X_2 and Z_2 are coordinates of points on the Planckian locus having helios of 75 blondels. The resulting change of adaptation is shown by the short curve in Fig. 9. The coordinates of the outer field are, of course, given by the Planckian curve shown in the figure, while the coordinates of the spot are indicated by a cross. The effect of the surround on adaptation is again seen to be small, amounting to a few minimum perceptible steps.

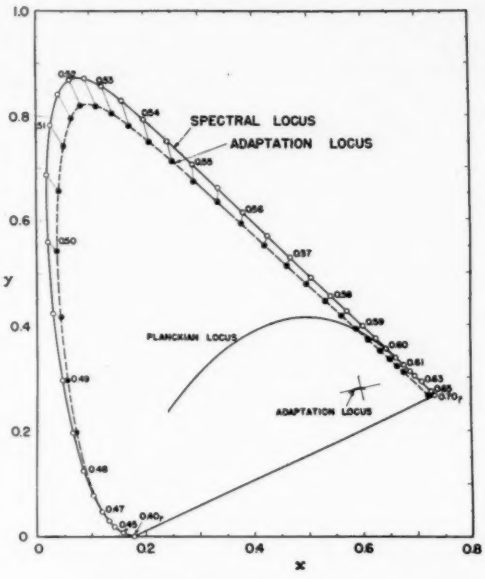

FIG. 9. The C.I.E. chromaticity diagram, showing the effect on adaptation of changing the colors of the outer and inner parts of the field.

6. EYE MOVEMENTS

In the previous sections, the assumption has been made that the eyes are absolutely fixed. But under ordinary conditions the eyes rove over a considerable space; and even if complete fixation is attempted, there are small involuntary movements of the eyes. The purpose of the present section is to investigate the effect of the eye movements on foveal adaptation.

With a non-uniform field, eye movements must necessarily cause transient effects in adaptation. But if the movements are sufficiently rapid in comparison with the velocity of the photochemical adaptation process, the adaptation level will fluctuate about a mean value and the amplitude of the fluctuations will be negligible. It is only this mean value that will be considered here.

It is convenient to take the center of the scene being viewed as the origin 0 of a coordinate system. If fixation is attempted, 0 will be the fixation point; and in this "equilibrium position," the shaded area of Fig. 10 will be imaged on the fovea. One may think of eye movements as causing the shaded area to move over the fixed scene, or one may hold 0 fixed and move the scene bodily with respect to the coordinate system so that the center of the scene shifts to 0′. The latter method will be used.

For each instantaneous position of the scene, there is a steady-state adaptation $H_A(\theta, \phi)$ which can be determined by the methods of the previous sections. When various positions follow each other in rapid succession, the eye will adapt itself to some sort of weighted average of the function

[17] P. Moon and D. E. Spencer, J. Opt. Soc. Am. **33**, 260 (1943).
[18] D. L. MacAdam, J. Opt. Soc. Am. **32**, 247 (1942).

$H_A(\theta, \phi)$. The weighting function depends on θ only, in accordance with the postulated axial symmetry of the eye. Thus the adaptation state

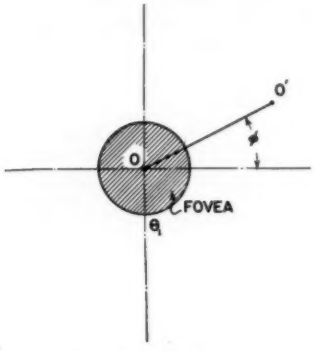

FIG. 10. Eye movements.

with rapid eye movements can be written

$$\bar{H}_A = K \int\int w(\theta) \cdot H_A(\theta, \phi) \cdot \theta \, d\theta \, d\phi, \qquad (26)$$

where $w(\theta)$ = weighting function, and

$$K = \left[\int\int w(\theta) \cdot \theta \, d\theta \, d\phi \right]^{-1}. \qquad (27)$$

Equation (26) is the general expression that applies to adaptation with any kind of rapid eye movements. Two special cases will be considered:

(1) Voluntary movements over a set of samples,

(2) Involuntary movements associated with fixation.

In the first case a decision must be made as to the range of eye movements and the relative time spent in different parts of the field. The former factor determines the limits of integration in Eqs. (26) and (27), while the latter determines the weighting function $w(\theta)$.

If the eye moves with constant velocity and the field has circular symmetry, Eq. (26) reduces to

$$\bar{H}_A = \frac{\int H_A(\theta) \theta \, d\theta}{\int \theta \, d\theta}. \qquad (26a)$$

For example, consider a field made up of two parts (Fig. 3) having helios values of H_1 and H_2 and subtending the angles Θ_3 and Θ_2. The eyes rove uniformly over the entire area. If $\Theta_1 \ll \Theta_3$ so that the gradual transition of $H_A(\theta)$ at the boundary can be neglected, then Eq. (26a) reduces to

$$\bar{H}_A = \frac{H_1 \int_0^{\Theta_3} \theta \, d\theta + H_2 \int_{\Theta_3}^{\Theta_2} \theta \, d\theta}{\int_0^{\Theta_2} \theta \, d\theta}$$

$$= \frac{H_1 \Theta_3^2 + H_2(\Theta_2^2 - \Theta_3^2)}{\Theta_2^2}. \qquad (26b)$$

This is the average helios over the larger disk, as would be expected.

The average helios is easily obtained also for a set of n samples having areas $S_1, S_2, \cdots, S_n$ exhibited on a background whose exposed area is S_{n+1}. The shapes, sizes, and arrangements of the samples can be chosen at will, provided the assumption is made that the eyes move uniformly over the ensemble. Then if the values of helios are $H_1, H_2, \cdots, H_{n+1}$, the adaptation helios is evidently

$$\bar{H}_A = \frac{\sum_1^{n+1} H_i S_i}{\sum_1^{n+1} S_i}. \qquad (26c)$$

An obvious extension can be made to the adaptation vector for chromatic samples.

The second case concerns *involuntary* eye movements. The point 0 (Fig. 10) is fixated and 0′ tends to be most frequently in the neighborhood of 0. Also, the frequency with which 0′ is at a given value of θ decreases rapidly as θ increases. Under these circumstances, a Gaussian distribution seems reasonable, and one may assume that

$$w(\theta) \cdot \theta = \exp(-\theta^2/2\sigma^2). \qquad (28)$$

Substitution in Eq. (26) gives

$$\bar{H}_A = \frac{\int\int \exp\left(-\frac{\theta^2}{2\sigma^2}\right) H_A(\theta, \phi) d\theta\, d\phi}{\int\int \exp\left(-\frac{\theta^2}{2\sigma^2}\right) d\theta\, d\phi}. \quad (29)$$

For example, in the special case of a small glare source of intensity I at an equilibrium angle θ from the line of sight,

$$H_s = (KI/r^2)(\cos\theta/\theta^2) \quad (30)$$

if the rest of the field is dark. (KI/r^2) is constant with respect to eye movements, and Eq. (29) becomes

$$H_A = \frac{\frac{KI}{r^2}\int \exp\left(-\frac{\theta^2}{2\sigma^2}\right)\frac{\cos\theta}{\theta^2} d\theta}{\exp\left(-\frac{\theta^2}{2\sigma^2}\right) d\theta}. \quad (31)$$

The integrals can be evaluated mechanically. Other cases can be worked out in a similar manner, though the results are complicated and ordinarily the integrals cannot be expressed in a simple analytical manner.

An important example is concerned with the change in adaptation level when the observer attempts to fixate a small circular spot on a background having a different helios. Suppose that the radius of the test spot subtends an angle of 1° and the radius of the outer part of the field is 30°. The trichromatic coordinates of the test spot are $X_1=316$, $Y_1=150$, $Z_1=64.2$, while those of the surrounding field are $X_2=71.3$, $Y_2=75.0$, $Z_2=88.4$. In investigating the effect of eye movements, one must calculate steady-state adaptation as a function of θ. This was computed by plotting curves of the integrand of Eqs. (8) and (21) and integrating by means of a planimeter. The results were substituted in Eq. (29). The value of σ refers to involuntary eye movements. According to Marshall and Talbot,[19] the range of physiological nystagmus is 30′. Taking this value as three times the standard deviation, we obtain

$$\sigma = 2.92\times10^{-3} \text{ radian},$$

and

$$\bar{H}_A = (2/\pi)^{\frac{1}{2}}\int_0^{\theta} \exp\left(-\frac{\theta^2}{2\sigma^2}\right) H_A(\theta) d\theta. \quad (32)$$

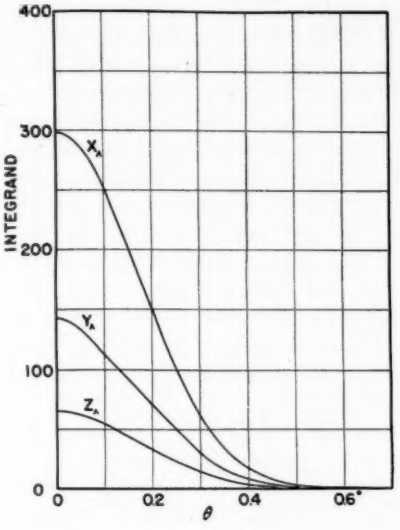

FIG. 11. Integrands of Eq. (32).

The integrands are shown in Fig. 11. Integration by planimeter gives the final result, $X_A=301$, $Y_A=142$, $Z_A=64.5$. This should be compared with the state of adaptation for no movement of the eyes: $X_A=298.5$, $Y_A=143$, $Z_A=65.2$. From this and similar computations, one can conclude that involuntary eye movements are of such small amplitude that they will ordinarily have negligible effect on foveal adaptation. There are presumably some unusual color distributions for which this is not true, but in most practical cases one can avoid the complexity of Eqs. (29) to (32) and can employ the simpler formulas of Section 5.

7. SUMMARY

The purpose of the paper is to investigate the specification of foveal adaptation. This specification is given in terms of the equivalent uniform field which would produce the same adaptation as the actual non-uniform field.

[19] W. H. Marshall and S. A. Talbot, Biol. Symposia **7**, 138 (1942).

The method is based on the experiments of Holladay, Stiles and Crawford, and others on the effect of a concentrated glare source. The experimental results on concentrated sources are then extended by integration to fields of larger size, and a general equation for the adaptation helios H_A is obtained for any distribution of field helios H. Simple equations are derived for a number of practical cases. For example, it is shown that with a dark surround, a uniform circular field of radius 28° produces an adaptation within 1 percent of that produced by a uniform disk covering the entire visual field.

The specification in terms of a single number H_A applies whenever all the parts of the field have essentially the same color quality. Where variations in color quality occur, the single-number specification of adaptation becomes inadequate. The scalar quantity H_A must then be replaced by a vector quantity having the trichromatic coordinates X_A, Y_A, Z_A. An example is given showing the variation in color adaptation when the C.I.E. coordinates of a circular test spot are changed while the surrounding field remains constant. Another example shows how the adaptation varies when the surround is changed for a fixed color spot.

Finally, the question of eye movements is considered. General expressions are obtained for the adaptation state with rapid eye movements. The use of these equations in a specific case ordinarily requires numerical integrations. That they can be carried through if necessary, however, is shown by an example. Numerical investigation indicates that in most practical cases the effect of involuntary eye movements on foveal adaptation is negligible.

The question may arise as to the validity of the rather elaborate superstructure which has been erected on the basis of Eq. (2). The foundation for this superstructure consists of the six postulates of Section 2. If these postulates are correct (and all experimental evidence indicates that they are correct, within the inherently large variation that will always occur because of the variability of the human organism), then the conclusions resulting from mathematical manipulations must also be correct.

In conclusion, we wish to emphasize the need for a more careful consideration of adaptation in visual tests. For instance, the earlier experimenters with visual acuity used a test spot with a dark surround and apparently concluded that the surround had negligible effect. Later investigations showed conclusively that the illumination of the surround was very important at the higher values of helios. Some of the most recent work has been done with careful attention to the maintenance of a uniform helios distribution over the complete field of view. But even today there is a lack of consideration of the exact state of foveal adaptation, particularly in research on color. Usually the experimenter does not use a simple arrangement of the visual field, and thus the calculation of foveal adaptation is difficult. In other cases insufficient data are given as to the arrangement of the field and the instructions of the observer concerning eye movements. In view of the importance of the subject, future experiments should be made with full cognizance of the state of adaptation.

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American Standard Dimensions of Photographic Papers

Inch Width Rolls

ASA
Reg. U. S. Pat. Off.
Z38.1.5-1943

1. Width

The nominal width of the paper should be accurate to plus zero, minus 1/32, inch.

2. Length

The length of the paper should be not less than the nominal length plus one wrap around the core and one wrap around the outside of the roll.

3. Allowance for Splices

On long rolls containing splices, one foot additional length should be given for each splice.

4. Method of Measuring

All measurements should be made after conditioning the sample in accordance with Official Standard T 402 m-41 of the Technical Association of the Pulp and Paper Industry, October 1941. In general, this requires four hours' conditioning of a freely suspended sample in an atmosphere maintained at 50 percent relative humidity and 23 C (73 F), the permissible tolerance being ±2 percent in relative humidity (48 to 52 percent) and ±2 degrees centigrade (3.5 degrees Fahrenheit) in temperature. Material from previously unopened packages should be used and the measurements made prior to the expiration date appearing on the original package.

Approved June 11, 1943 by American Standards Association.
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This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions of Photographic Papers

Centimeter Size Sheets and Rolls

ASA
Reg. U. S. Pat. Off.
Z38.1.6-1943

1. Cut Sheets

1.1 Nominal Size	Tolerance
65× 95 mm	+0, −1 mm
70×115 mm	+0, −1 mm
74×105 mm	+0, −1 mm
90×140 mm	+0, −1 mm
100×150 mm	+0, −1 mm
180×180 mm	+0, −1 mm
300×400 mm	+0, −2 mm
500×600 mm	+0, −2 mm

1.2 Method of Measuring. All measurements should be made after conditioning the sample in accordance with Official Standard T 402 m-41 of the Technical Association of the Pulp and Paper Industry, October 1941. In general, this requires four hours' conditioning of a freely suspended sample in an atmosphere maintained at 50 percent relative humidity and 23 C (73 F), the permissible tolerance being ±2 percent in relative humidity (48 to 52 percent) and ±2 degrees centigrade (3.5 degrees Fahrenheit) in temperature. Material from previously unopened packages should be used and the measurements made prior to the expiration date appearing on the original package.

2. Rolls

2.1 Nominal Width	Tolerance
35 mm	+0, −1 mm
45 mm	+0, −1 mm
60 mm	+0, −1 mm
120 mm	+0, −1 mm
150 mm	+0, −1 mm
300 mm	+0, −2 mm

2.2 Length of Rolls. The length of the paper should be not less than the nominal length plus one wrap around the core and one wrap around the outside of the roll.

2.3 Allowance for Splices. On long rolls containing splices, 30 cm additional length should be given for each splice.

2.4 Method of Measuring. Same as 1.2, above.

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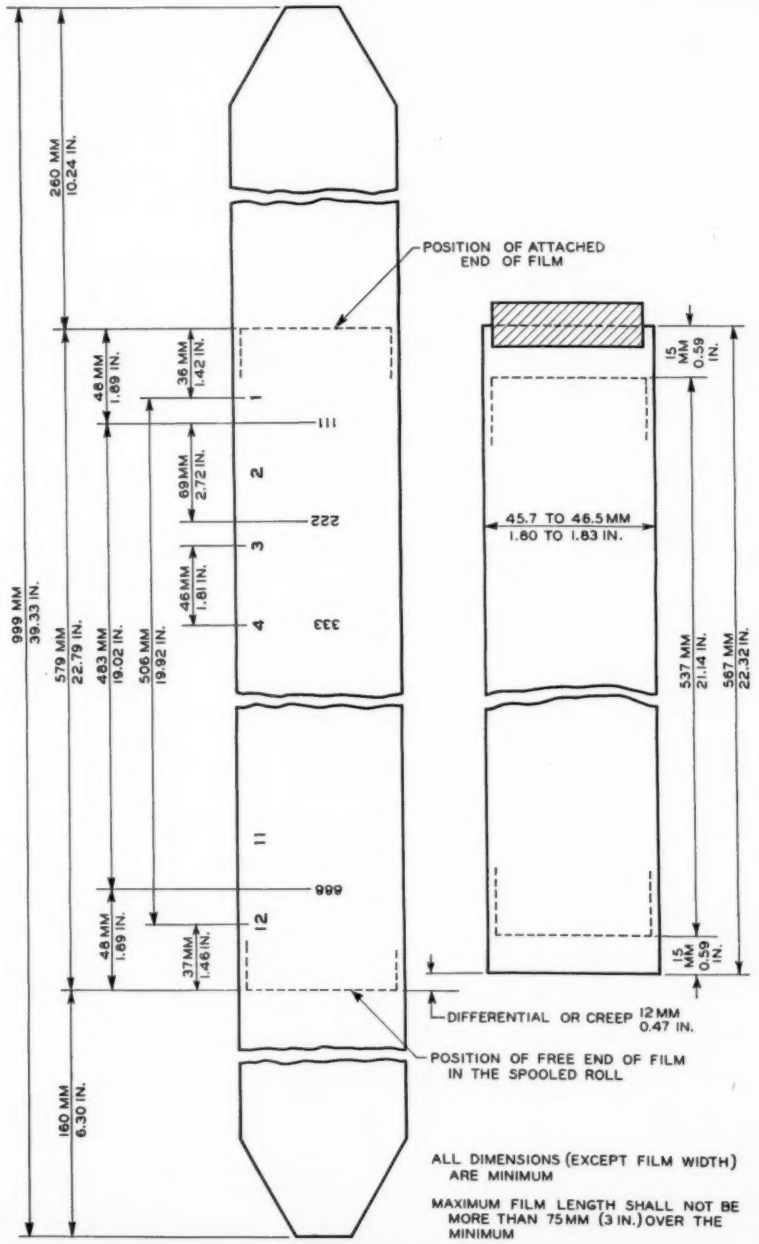
American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 1

ASA
Reg. U. S. Pat. Off.
Z38.1.7-1943

Designated by American Manufacturers as: A-8; 127; G-27; 27; S-27 when wound on spool Z38.1.16-1943.



Z38.1.7—Z38.1.24-1943, approved June 11, 1943, by American Standards Association.
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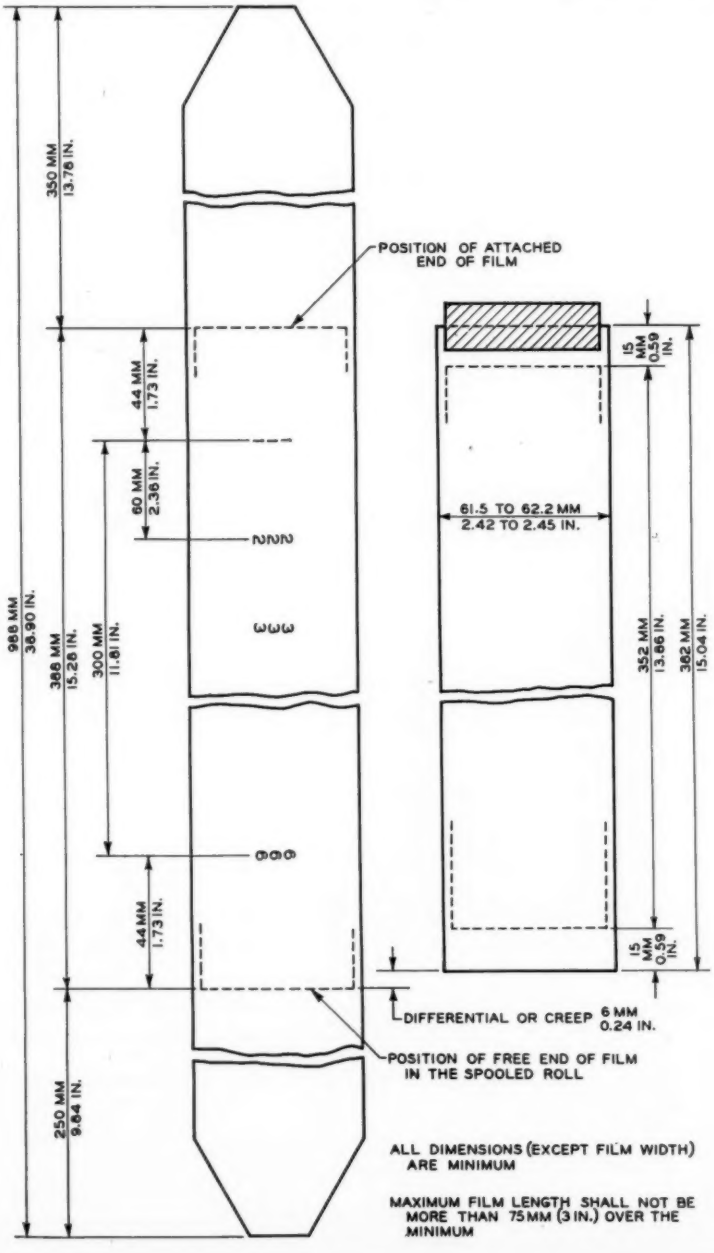
American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 2

ASA
Reg. U. S. Pat. Off.
Z38.1.8-1943

Designated by American Manufacturers as: B-1; 117 when wound on spool Z38.1.17-1943.

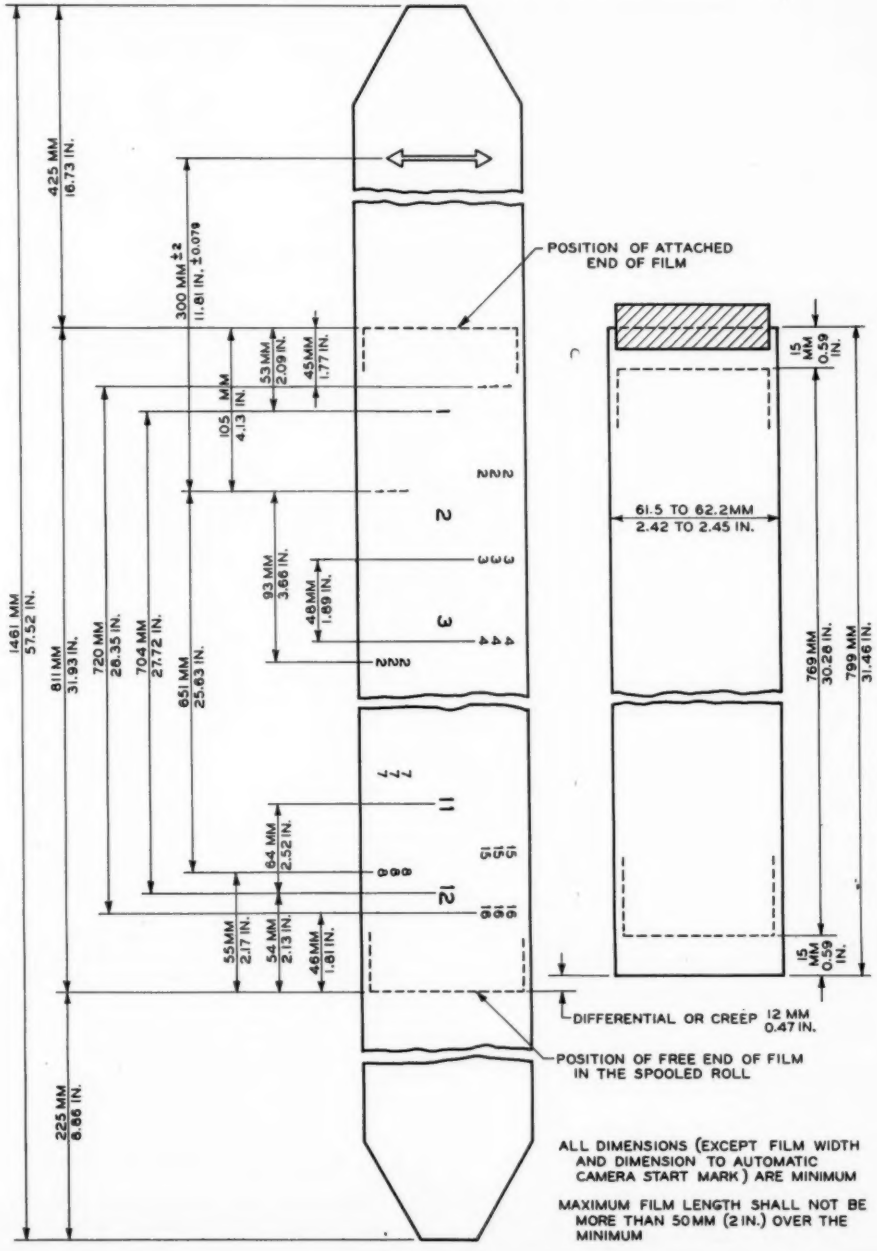

350 MM
13.78 IN.
POSITION OF ATTACHED END OF FILM
15 MM 0.59 IN.
44 MM 1.73 IN.
60 MM 2.36 IN.
61.5 TO 62.2 MM
2.42 TO 2.45 IN.
988 MM 38.90 IN.
388 MM 15.26 IN.
300 MM 11.81 IN.
352 MM 13.86 IN.
382 MM 15.04 IN.
44 MM 1.73 IN.
15 MM 0.59 IN.
DIFFERENTIAL OR CREEP 6 MM 0.24 IN.
POSITION OF FREE END OF FILM IN THE SPOOLED ROLL
250 MM 9.84 IN.
ALL DIMENSIONS (EXCEPT FILM WIDTH) ARE MINIMUM
MAXIMUM FILM LENGTH SHALL NOT BE MORE THAN 75 MM (3 IN.) OVER THE MINIMUM

This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 3

ASA
Reg. U. S. Pat. Off.
Z38.1.9-1943

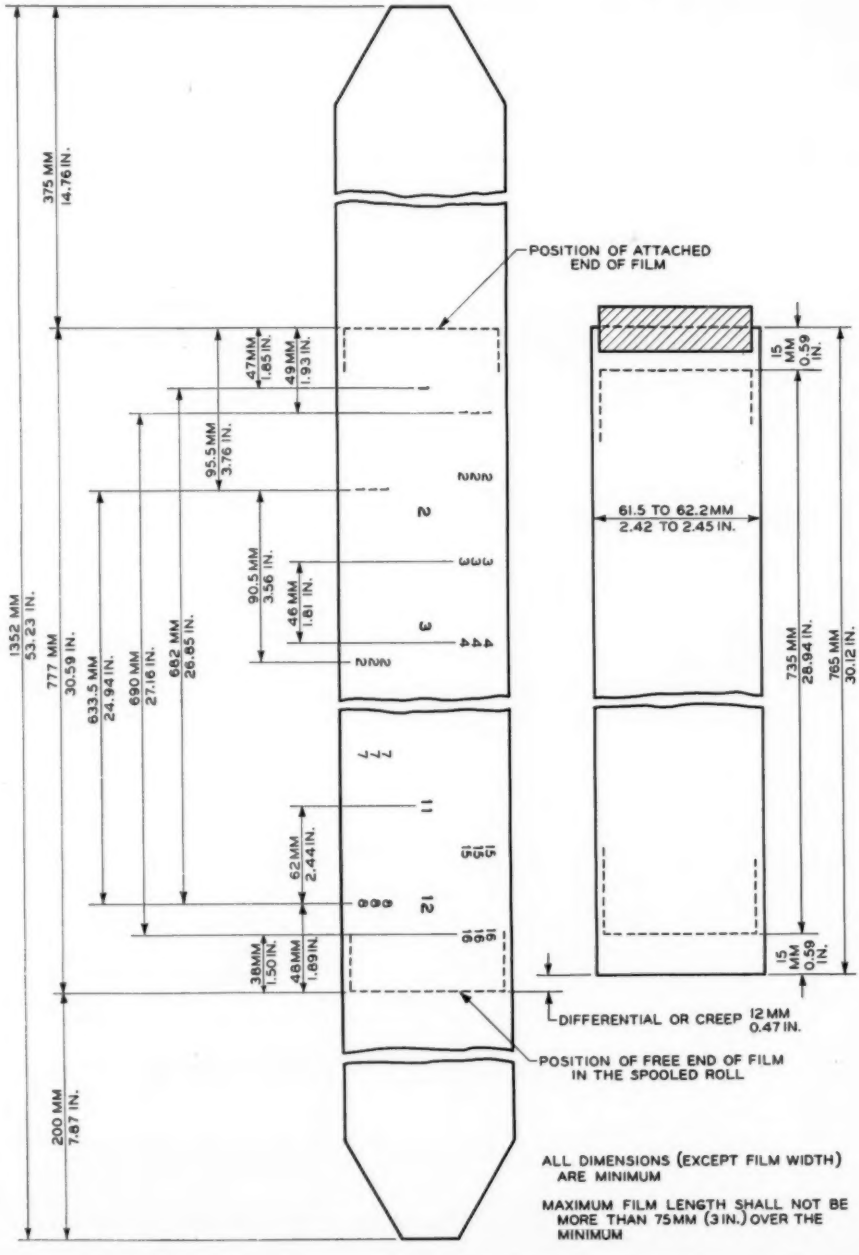
Designated by American Manufacturers as: B-2; 120; G-20; 20; S-20 when wound on spool Z38.1.18-1943.


425 MM 16.73 IN.
300 MM ±2 11.81 IN. ±0.079
POSITION OF ATTACHED END OF FILM
53 MM 2.09 IN.
45 MM 1.77 IN.
105 MM 4.13 IN.
93 MM 3.66 IN.
48 MM 1.89 IN.
84 MM 2.52 IN.
55 MM 2.17 IN.
54 MM 2.13 IN.
46 MM 1.81 IN.
1461 MM 57.52 IN.
811 MM 31.93 IN.
720 MM 28.35 IN.
704 MM 27.72 IN.
651 MM 25.63 IN.
225 MM 8.86 IN.
61.5 TO 62.2 MM 2.42 TO 2.45 IN.
15 MM 0.59 IN.
769 MM 30.28 IN.
799 MM 31.46 IN.
DIFFERENTIAL OR CREEP 12 MM 0.47 IN.
POSITION OF FREE END OF FILM IN THE SPOOLED ROLL
ALL DIMENSIONS (EXCEPT FILM WIDTH AND DIMENSION TO AUTOMATIC CAMERA START MARK) ARE MINIMUM
MAXIMUM FILM LENGTH SHALL NOT BE MORE THAN 50 MM (2 IN.) OVER THE MINIMUM

American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 4

ASA
Reg. U. S. Pat. Off.
Z38.1.10-1943

Designated by American Manufacturers as: PB-20; 620; G-6-20; S-620 when wound on spool Z38.1.19-1943.

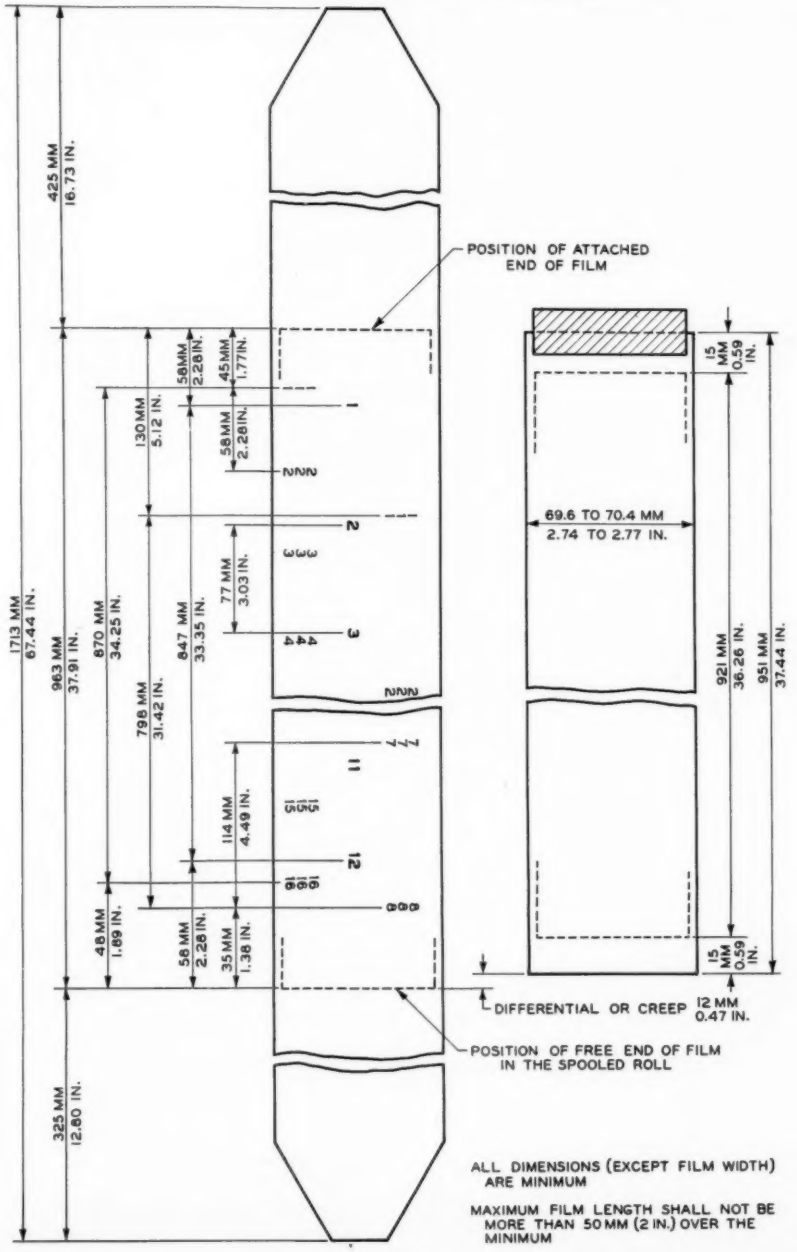


This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 5

ASA
Reg. U. S. Pat. Off.
Z38.1.11-1943

Designated by American Manufacturers as: D-6; 116; G-16; 16; S-16 when wound on spool Z38.1.20-1943; PD-16; 616; G-6-16; S-616 when wound on spool Z38.1.21-1943.

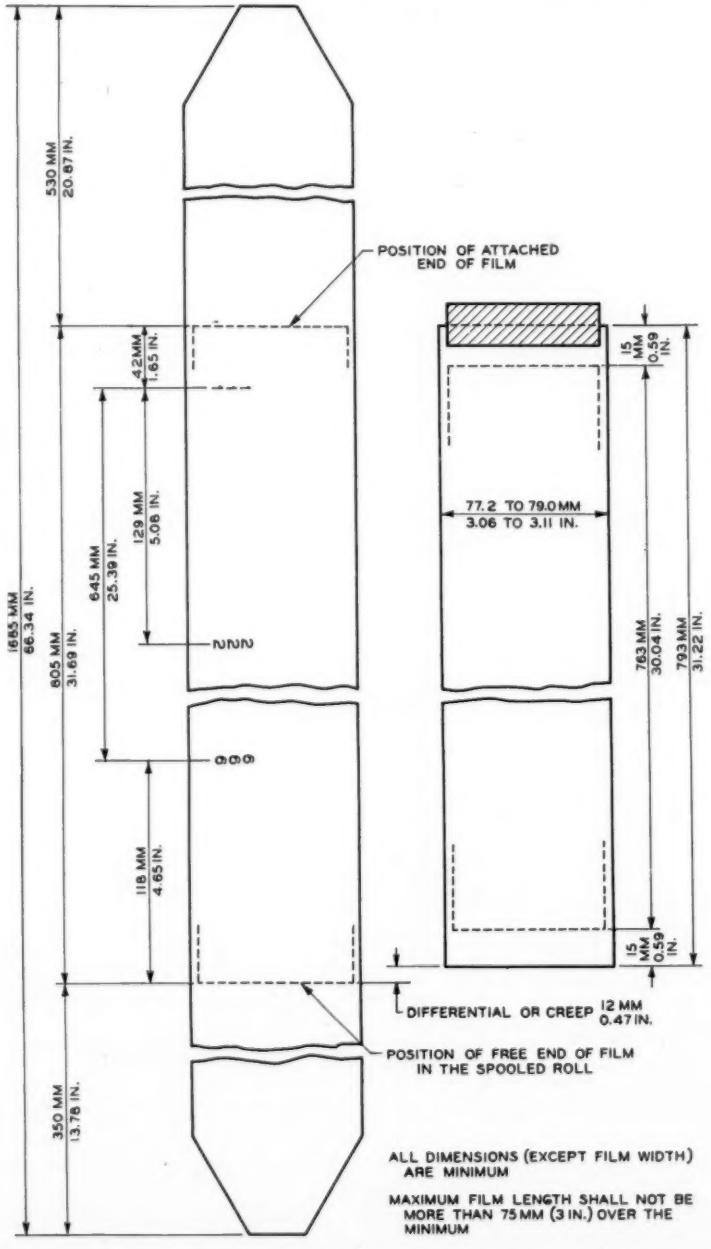

425 MM
16.73 IN.
POSITION OF ATTACHED END OF FILM
58MM 2.28IN.
45MM 1.77IN.
130MM 5.12 IN.
58MM 2.28IN.
69.6 TO 70.4 MM
2.74 TO 2.77 IN.
77 MM 3.03 IN.
1713 MM 67.44 IN.
963 MM 37.91 IN.
870 MM 34.25 IN.
847 MM 33.35 IN.
798 MM 31.42 IN.
114 MM 4.49 IN.
48 MM 1.89 IN.
56 MM 2.28 IN.
35 MM 1.38 IN.
15 MM 0.59 IN.
921 MM 36.26 IN.
951 MM 37.44 IN.
15 MM 0.59 IN.
DIFFERENTIAL OR CREEP 12 MM 0.47 IN.
POSITION OF FREE END OF FILM IN THE SPOOLED ROLL
325 MM 12.80 IN.
ALL DIMENSIONS (EXCEPT FILM WIDTH) ARE MINIMUM
MAXIMUM FILM LENGTH SHALL NOT BE MORE THAN 50 MM (2 IN.) OVER THE MINIMUM

This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 6

ASA
Reg. U. S. Pat. Off.
Z38.1.12-1943

Designated by American Manufacturers as: M-6; 130; G-30; 30; S-30 when wound on spool Z38.1.22-1943.



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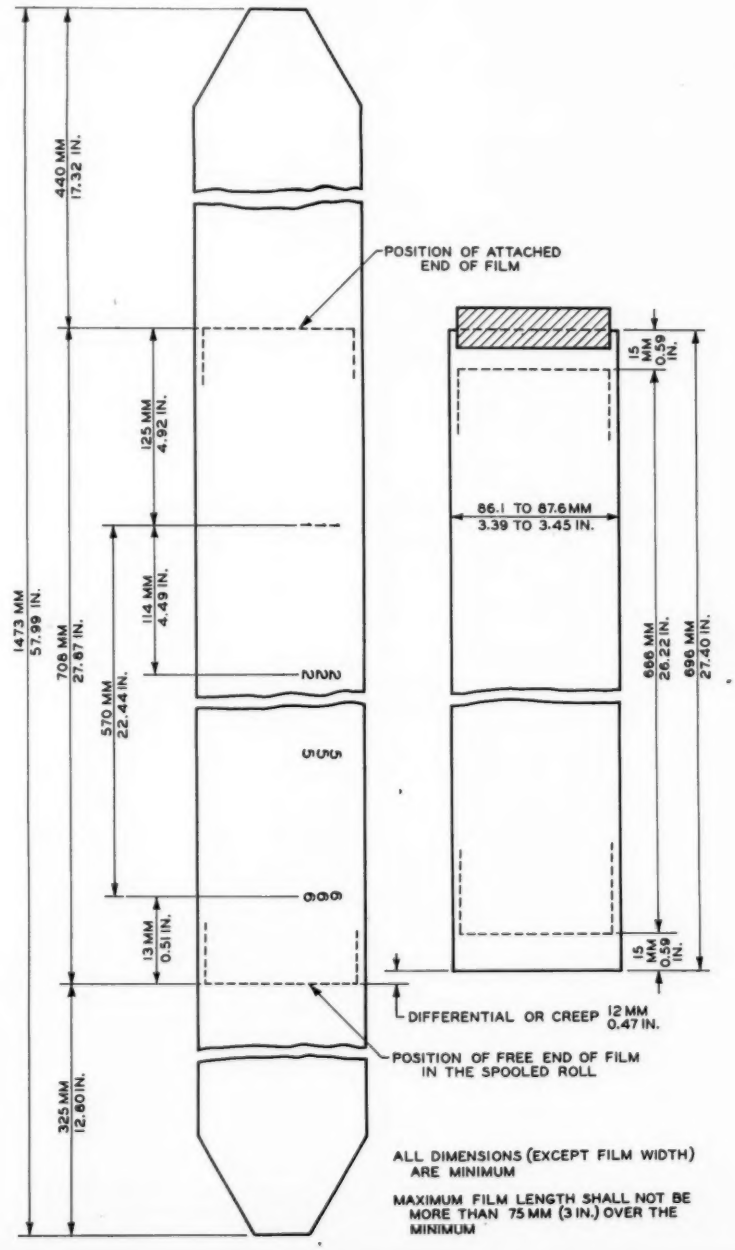
American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 7

ASA
Reg. U. S. Pat. Off.
Z38.1.13-1943

Designated by American Manufacturers as: E-6; 118; G-18; 18; S-18 when wound on spool Z38.1.23-1943.


440 MM 17.32 IN.
POSITION OF ATTACHED END OF FILM
15 MM 0.59 IN.
125 MM 4.92 IN.
86.1 TO 87.6 MM 3.39 TO 3.45 IN.
1473 MM 57.99 IN.
706 MM 27.87 IN.
114 MM 4.49 IN.
570 MM 22.44 IN.
666 MM 26.22 IN.
696 MM 27.40 IN.
13 MM 0.51 IN.
15 MM 0.59 IN.
DIFFERENTIAL OR CREEP 12 MM 0.47 IN.
POSITION OF FREE END OF FILM IN THE SPOOLED ROLL
325 MM 12.80 IN.
ALL DIMENSIONS (EXCEPT FILM WIDTH) ARE MINIMUM
MAXIMUM FILM LENGTH SHALL NOT BE MORE THAN 75 MM (3 IN.) OVER THE MINIMUM

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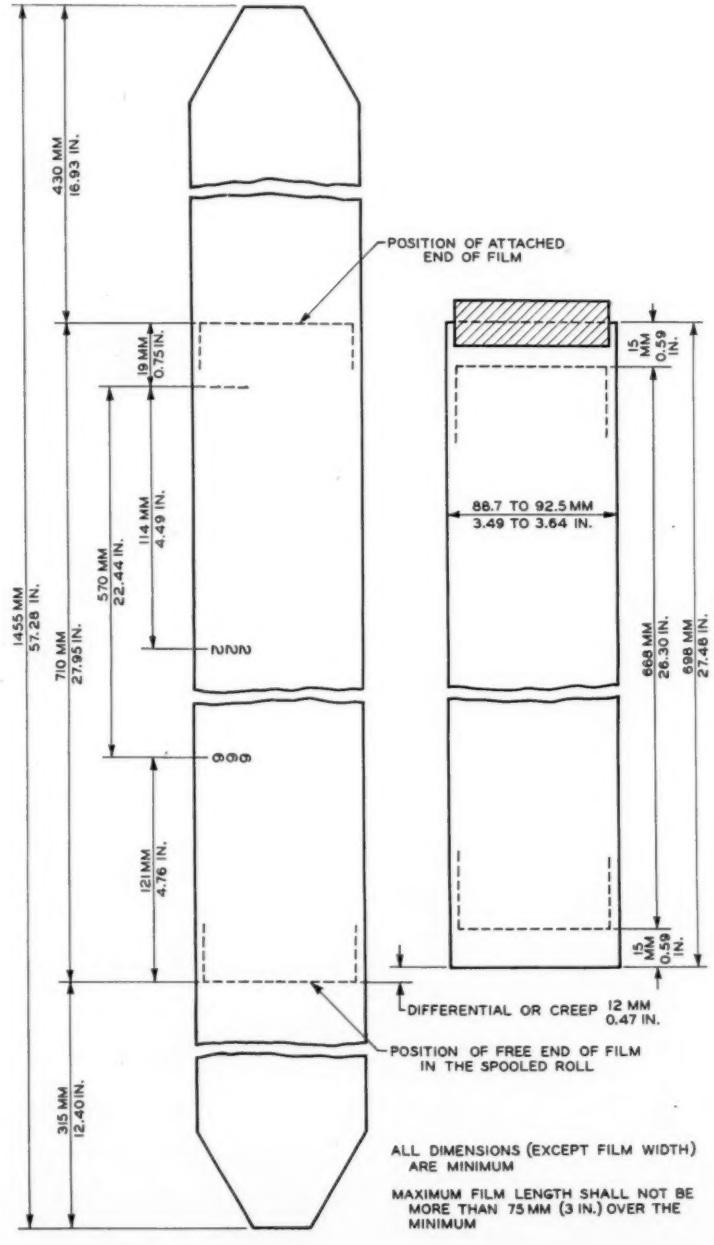
American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 8

ASA
Reg. U. S. Pat. Off.
Z38.1.14-1943

Designated by American Manufacturers as: F-6; 124; G-24; 24 when wound on spool Z38.1.24-1943.



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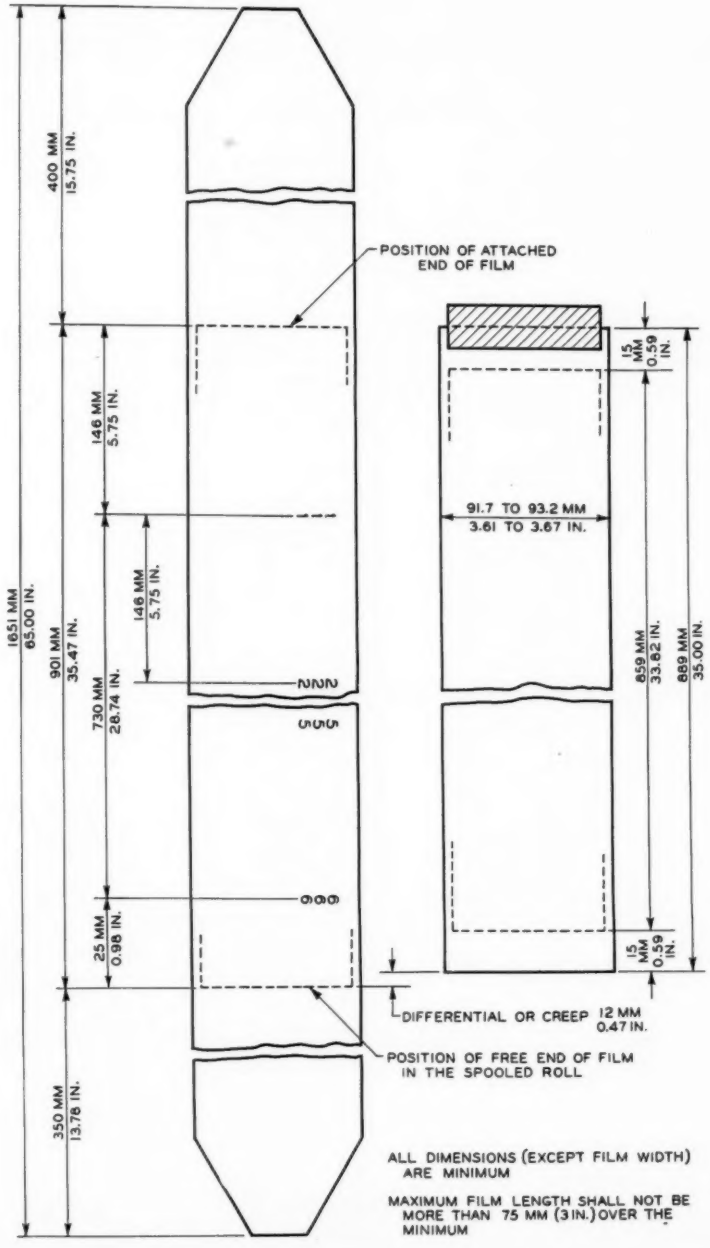
American Standard Dimensions for Amateur Roll Film and Backing Paper—No. 9

ASA
Reg. U. S. Pat. Off.
Z38.1.15-1943

Designated by American Manufacturers as: G-6; 122; G-22; 22; S-22 when wound on spool Z38.1.24-1943.


400 MM
15.75 IN.
POSITION OF ATTACHED END OF FILM
15 MM 0.59 IN.
146 MM 5.75 IN.
91.7 TO 93.2 MM
3.61 TO 3.67 IN.
146 MM 5.75 IN.
1651 MM 65.00 IN.
901 MM 35.47 IN.
730 MM 28.74 IN.
859 MM 33.82 IN.
889 MM 35.00 IN.
25 MM 0.98 IN.
15 MM 0.59 IN.
DIFFERENTIAL OR CREEP 12 MM 0.47 IN.
POSITION OF FREE END OF FILM IN THE SPOOLED ROLL
350 MM 13.78 IN.
ALL DIMENSIONS (EXCEPT FILM WIDTH) ARE MINIMUM
MAXIMUM FILM LENGTH SHALL NOT BE MORE THAN 75 MM (3 IN.) OVER THE MINIMUM

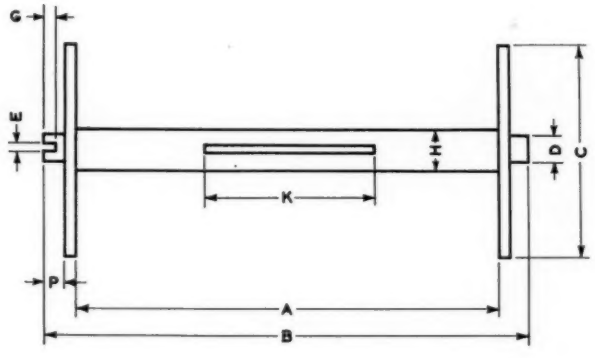
This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film Spools—No. 1

ASA
Reg. U. S. Pat. Off.
Z38.1.16-1943

Designated by American Manufacturers as:
A-8; 127; G-27; 27; S-27

Used in cameras with nominal picture size:
$1\frac{5}{8} \times 2\frac{1}{2}$ in.
$1\frac{5}{8} \times 1\frac{5}{8}$ in.
30×40 mm



Description		In.	Mm
A	Max	1.864	47.35
	Min	1.854	47.09
B	Max	2.179	55.35
	Min	2.138	54.31
C	Max	0.756	19.2
	Min	0.740	18.8
D	Max	0.157	3.99
	Min	0.146	3.71

Description		In.	Mm
E	Max	0.063	1.60
	Min	0.043	1.09
G	Min	0.100	2.54
H	Max	0.191	4.85
	Min	0.185	4.70
K	Min	0.787	20.0
N	Tol	0.010	0.254
P	Max	0.130	3.30
	Min	0.118	3.00

N = Concentricity of C and H

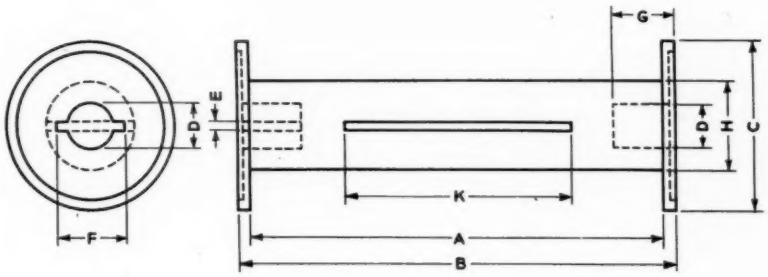
This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film Spools—No. 2

ASA
Reg. U. S. Pat. Off.
Z38.1.17-1943

Designated by American Manufacturers as:
B-1; 117

Used in cameras with nominal picture size:
2¼×2¼ in.



Description		In.	Mm
A	Max	2.478	62.94
	Min	2.465	62.61
B*	Max	2.602	66.09
	Min	2.577	65.45
C	Max	0.880	22.35
	Min	0.866	22.00
D	Max	0.216	5.50
	Min	0.201	5.10

Description		In.	Mm
E	Max	0.110	2.79
	Min	0.075	1.91
F	Min	0.374	9.50
G	Min	0.354	8.99
H	Max	0.476	12.09
	Min	0.441	11.20
K	Min	1.177	29.90
M	Tol	0.010	0.254
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

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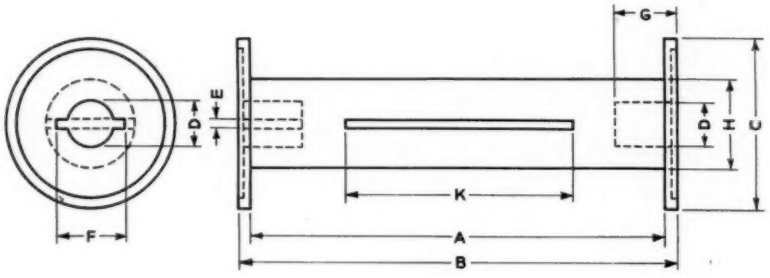
American Standard Dimensions for Amateur Roll Film Spools—No. 3

ASA
Reg. U. S. Pat. Off.
Z38.1.18-1943

Designated by American Manufacturers as:
B-2; 120; G-20; 20; S-20

Used in cameras with nominal picture size:
$2\frac{1}{4} \times 3\frac{1}{4}$ in.
$2\frac{1}{4} \times 2\frac{1}{4}$ in.
$1\frac{5}{8} \times 2\frac{1}{4}$ in.



Description		In.	Mm
A	Max	2.478	62.94
	Min	2.465	62.61
B*	Max	2.602	66.09
	Min	2.577	65.45
C	Max	0.998	25.35
	Min	0.984	25.00
D	Max	0.216	5.50
	Min	0.201	5.10

Description		In.	Mm
E	Max	0.110	2.79
	Min	0.087	2.21
F	Min	0.390	9.91
G	Min	0.354	8.99
H	Max	0.476	12.09
	Min	0.441	11.20
K	Min	1.177	29.90
M	Tol	0.010	0.254
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

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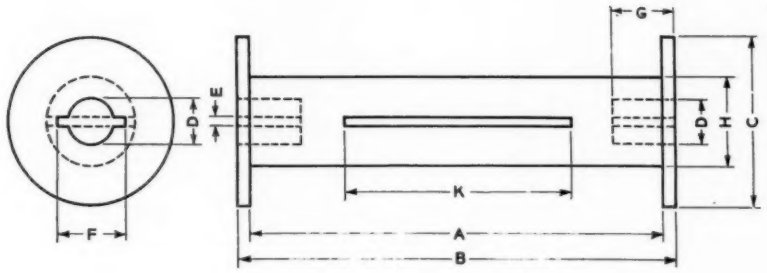
American Standard Dimensions for Amateur Roll Film Spools—No. 4

ASA
Reg. U. S. Pat. Off.
Z38.1.19-1943

Designated by American Manufacturers as:
PB-20; 620; G6-20; S-620

Used in cameras with nominal picture size:
$2\frac{1}{4}\times3\frac{1}{4}$ in.
$2\frac{1}{4}\times2\frac{1}{4}$ in.
$1\frac{5}{8}\times2\frac{1}{4}$ in.



Description		In.	Mm
A	Max	2.478	62.94
	Min	2.465	62.61
B*	Max	2.522	64.06
	Min	2.500	63.50
C	Max	0.911	23.15
	Min	0.898	22.80
D	Max	0.161	4.09
	Min	0.154	3.91

Description		In.	Mm
E	Max	0.079	2.01
	Min	0.067	1.70
F	Min	0.240	6.10
G	Min	0.157	3.99
H	Max	0.287	7.29
	Min	0.276	7.01
K	Min	1.362	34.60
M	Tol	0.005	0.127
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

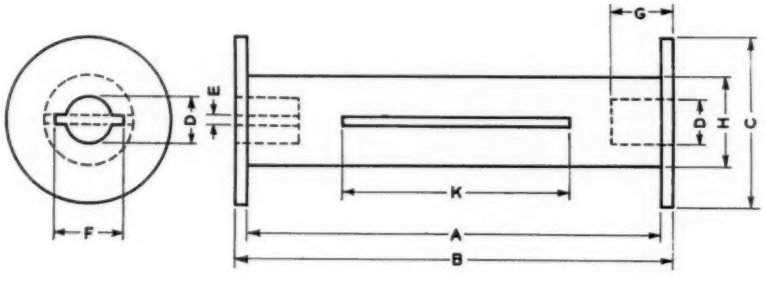
This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film Spools—No. 5

ASA
Reg. U. S. Pat. Off.
Z38.1.20-1943

Designated by American Manufacturers as:
D-6; 116; G-16; 16; S-16

Used in cameras with nominal picture size:
$2\frac{1}{2} \times 4\frac{1}{4}$ in.
$2\frac{1}{2} \times 2\frac{7}{8}$ in.
$2\frac{1}{2} \times 2\frac{1}{8}$ in.



Description		In.	Mm
A	Max	2.823	71.70
	Min	2.809	71.35
B*	Max	2.867	72.82
	Min	2.844	72.25
C	Max	1.252	31.80
	Min	1.236	31.40
D	Max	0.173	4.39
	Min	0.150	3.81

Description		In.	Mm
E	Max	0.110	2.79
	Min	0.075	1.91
F	Min	0.390	9.91
G	Min	0.374	9.50
H	Max	0.476	12.09
	Min	0.441	11.20
K	Min	1.260	32.00
M	Tol	0.010	0.254
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

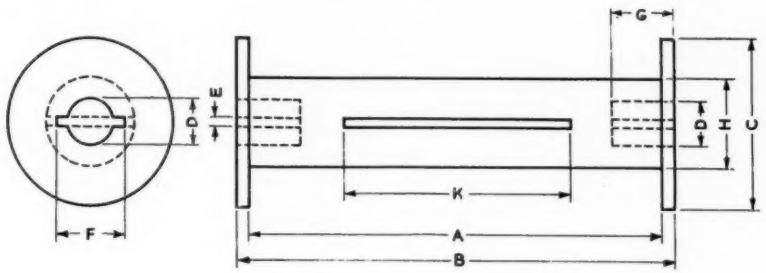
This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film Spools—No. 6

ASA
Reg. U. S. Pat. Off.
Z38.1.21-1943

Designated by American Manufacturers as:
PD-16; 616; G6-16; S-616

Used in cameras with nominal picture size:
$2\frac{1}{2} \times 4\frac{1}{4}$ in.
$2\frac{1}{2} \times 2\frac{7}{8}$ in.
$2\frac{1}{2} \times 2\frac{1}{8}$ in.



Description		In.	Mm
A	Max	2.823	71.70
	Min	2.809	71.35
B*	Max	2.867	72.82
	Min	2.844	72.25
C	Max	0.959	24.35
	Min	0.945	24.00
D	Max	0.161	4.09
	Min	0.154	3.91

Description		In.	Mm
E	Max	0.079	2.01
	Min	0.067	1.70
F	Min	0.240	6.10
G	Min	0.157	3.99
H	Max	0.287	7.29
	Min	0.276	7.01
K	Min	1.693	43.00
M	Tol	0.005	0.127
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

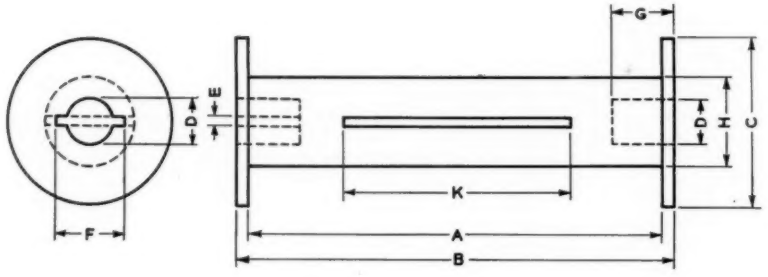
This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film Spools—No. 7

ASA
Reg. U. S. Pat. Off.
Z38.1.22-1943

Designated by American Manufacturers as:
M-6; 130; G-30; 30; S-30

Used in cameras with nominal picture size:
$2\frac{1}{4} \times 4\frac{1}{4}$ in.



Description		In.	Mm
A	Max	3.140	79.75
	Min	3.126	79.40
B*	Max	3.187	80.95
	Min	3.163	80.35
C	Max	1.252	31.80
	Min	1.236	31.40
D	Max	0.224	5.70
	Min	0.201	5.10

Description		In.	Mm
E	Max	0.110	2.79
	Min	0.075	1.91
F	Min	0.390	9.90
G	Min	0.374	9.50
H	Max	0.476	12.09
	Min	0.441	11.20
K	Min	1.260	32.00
M	Tol	0.010	0.254
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

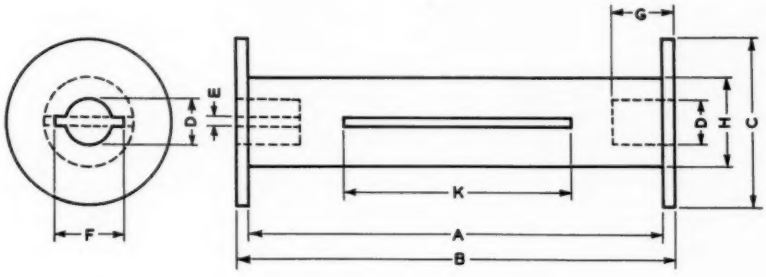
This publication is one of a series of American Standards for Photography (other than Cinematography).

American Standard Dimensions for Amateur Roll Film Spools—No. 8

ASA
Reg. U. S. Pat. Off.
Z38.1.23-1943

Designated by American Manufacturers as:
E-6; 118; G-18; 18; S-18

Used in cameras with nominal picture size:
$3\frac{1}{4} \times 4\frac{1}{4}$ in.



Description		In.	Mm
A	Max	3.482	88.45
	Min	3.469	88.10
B*	Max	3.530	89.65
	Min	3.506	89.05
C	Max	1.252	31.80
	Min	1.236	31.40
D	Max	0.224	5.70
	Min	0.201	5.10

Description		In.	Mm
E	Max	0.110	2.79
	Min	0.075	1.91
F	Min	0.390	9.90
G	Min	0.374	9.50
H	Max	0.476	12.09
	Min	0.441	11.20
K	Min	1.260	32.00
M	Tol	0.010	0.254
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

This publication is one of a series of American Standards for Photography (other than Cinematography).

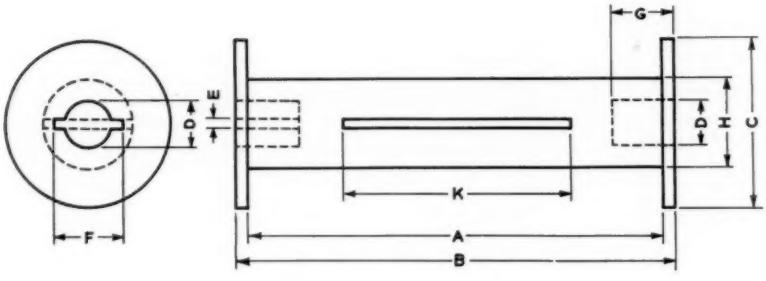
American Standard Dimensions for Amateur Roll Film Spools—No. 9

ASA
Reg. U. S. Pat. Off.
Z38.1.24-1943

Designated by American Manufacturers as: — Used in cameras with nominal picture size:

F-6; 124; G-24; 24 ⟷ $3\frac{1}{4} \times 4\frac{1}{4}$ in.

G-6; 122; G-22; 22; S-22 ⟷ $3\frac{1}{4} \times 5\frac{1}{2}$ in.



Description		In.	Mm
A	Max	3.721	94.50
	Min	3.707	94.15
B*	Max	3.768	95.70
	Min	3.744	95.10
C	Max	1.252	31.80
	Min	1.236	31.40
D	Max	0.224	5.70
	Min	0.201	5.10

Description		In.	Mm
E	Max	0.110	2.79
	Min	0.075	1.91
F	Min	0.390	9.90
G	Min	0.374	9.50
H	Max	0.476	12.09
	Min	0.441	11.20
K	Min	1.260	32.00
M	Tol	0.010	0.254
N	Tol	0.010	0.254

M = Concentricity of D and C
N = Concentricity of C and H

* These dimensions are for spooled film at 45 to 55 percent relative humidity.

Appendix

To Z38.1.7-Z38.1.24

A1. Definition of Terms

AMATEUR roll films consist of three essential parts: a spool, a length of photographic film, and a backing paper. In the present body of standards, maximum and minimum dimensions are given for the film strip and spool, and minimum dimensions only for the backing paper.

In order to clarify the standards, the following definitions of terms are given.

Backing Paper (also called Duplex Paper)—The protective strip of paper to which the film is attached. Backing paper is usually black on one side and colored on the opposite side. Numerals are usually printed on the colored side in a position where they can be viewed through the camera window.

Core of a Spool—The cylindrical part extending between and connecting the flanges, around which the backing paper and film are wound.

Creep—The difference in location of the film end relative to the numbers on the backing paper when they are wound on the spool, compared to the respective positions when laid out flat. This difference exists because the backing paper, being wound outside the film strip, assumes a curve of greater circumference than the film strip for each successive convolution.

End Margin—The distance from the end of the last picture to the end of the film strip. Included in the end margin is an allowance for attaching a developing clip.

Exposure Numbers—Consecutive numbers or sets of numbers printed on the outside of the backing paper away from the film (usually on the colored side), which serve to determine the spacing of the exposures as these numbers are brought into position successively in the window of the camera. Some sizes of amateur roll film bear more than one series of numbers, each series being associated with a particular picture size, and hence with cameras producing negatives of that size. Proper positioning of the window in the camera permits the use of the proper series of numbers for the picture size appropriate to that camera. For example, the film and backing paper represented by Z38.1.9-1943 are adapted for use in three types of cameras taking different picture sizes and bear exposure numbers for eight pictures $2\frac{1}{4} \times 3\frac{1}{4}$ in., twelve pictures $2\frac{1}{4} \times 2\frac{1}{4}$ in., or sixteen pictures $1\frac{5}{8} \times 2\frac{1}{4}$ in.

Film—The sensitized material which receives the photographic image in the camera. Amateur roll film usually consists of a gelatin-silver bromide emulsion coated on one side of a transparent cellulose plastic base about 0.003 inch thick, with a gelatin layer on the opposite side to counteract curl. The sensitive layer, however, may be coated on other base materials.

Flanges of a Spool—The disks attached to each end of the spool core, between which the film and backing paper are wound. The main function of the flanges is to prevent light from reaching the edges of the film.

Flat Film—The plane position of the film convenient for measuring, as distinguished from the position assumed by the film with relation to the backing paper as they are wound from one spool to the other in the camera.

Hub of a Spool—A projection beyond the flange of some spools, used as a bearing or support for the spool while in the camera. One hub usually contains a slot or other means for turning the spool.

Key Slot—See "Turning Slot."

Length of Film—The linear lengthwise dimension of the film strip. Four lengths are recognized in these standards: the minimum and maximum over-all length when flat; the minimum projected length; and the minimum utilizable length (see definition).

Minimum Dimension—The lower limiting dimensions for film and backing paper as specified in these standards. In practice, many of the minimum dimensions for film and backing paper will normally be exceeded by the several manufacturers because of manufacturing tolerances and for safety margin.

Paper Slots—Slots or openings in the core for attaching the backing paper leader preliminary to winding in the camera. The same slots are used by the manufacturer for winding the paper and film on the spool.

Projected Film Length—A dimension which shows the distance, measured along the backing paper, between the two ends of the film when wound on the spool. The projected film length is the flat film length plus the creep.

Roll Film—A daylight-loading supply of photographic film for use in hand-held still-picture cameras. It comprises a spool with solid opaque flanges on which is wound a continuous strip of backing paper having a substantially shorter strip of film attached to it in a definite position relative to the exposure numbers printed on the opposite side of the paper. Amateur roll film is distinguished from aerial, Cirkut, or miniature camera film roll, which may have paper leaders and trailers spliced to the film, but which do not have backing paper as herein defined.

Spool for Roll Film—A core assembled to two solid opaque flanges between which a strip of film with backing paper can be wound to comprise a roll film. A slot or the equivalent is provided in at least one end of the spool for engaging the winding key of the camera.

Start Margin—The distance from the beginning of the film to the beginning of the first exposure. Included in the start margin is an allowance for attaching a developing clip.

Turning Slot (also called Key Slot)—A slot in at least one end of the spool which is engaged by the winding key of the camera. This slot may be in the flange or hub of the spool.

Utilizable Film Length—That portion of the film length that is utilized for exposing the pictures. It represents the film exclusive of start and end margins, and is indicated on the standard sheets by the dotted sections at each end of the film strip.

Window (of Camera)—The colored transparent window (usually red) normally located in the back of a camera, through which the numbers on the backing paper can be seen as the film is wound through the camera.

A2. Designations Indicating Size of American-Made Amateur Roll Films

Nominal Picture Size (in Inches)	Brand Name				
	Agfa Ansco	Eastman Kodak	Gevaert	R. H. Macy and Co.	Sears, Roebuck
$1\frac{5}{8}\times2\frac{1}{2}$	A-8	127	G-27	27	S-27
$2\frac{1}{4}\times2\frac{1}{4}$	B-1	117	——	—	——
$2\frac{1}{4}\times3\frac{1}{4}$	B-2	120	G-20	20	S-20
$2\frac{1}{4}\times3\frac{1}{4}$	PB-20	620	G-6-20	620	S-620
$2\frac{1}{2}\times4\frac{1}{4}$	D-6	116	G-16	16	S-16
$2\frac{1}{2}\times4\frac{1}{4}$	PD-16	616	G-6-16	616	S-616
$3\frac{1}{4}\times4\frac{1}{4}$	E-6	118	G-18	18	S-18
$3\frac{1}{4}\times4\frac{1}{4}$	F-6	124	G-24	24	——
$2\frac{7}{8}\times4\frac{7}{8}$	M-6	130	G-30	30	S-30
$3\frac{1}{4}\times5\frac{1}{2}$	G-6	122	G-22	22	S-22

American Standard Method for Determining Photographic Speed and Speed Number

Foreword

This American Standard describes a sensitometric method of determining and expressing the photographic speed of roll films, film packs, and miniature camera films. It is believed that the method represents an improvement over other commonly used procedures, since it more fully satisfies the two fundamental requirements of a system to be adopted as a national standard: (1) The method must give results which can be applied directly and significantly to picture-taking practice. (2) The method must be simple to operate and must give unequivocal results.

The standard applies to individual samples and to a product as a whole. The sensitometric criterion upon which the method is based was first suggested by experimental work reported in various technical journals.* The British Standards Institution first proposed the technique for development used herein, which is included with the consent of that institution.

A preliminary draft of this standard, describing the method of determining the speed of a specific sample of film, was published in December, 1940 for trial and criticism. In line with suggestions based upon experience gained by use of the proposed specifications, the standard has received minor revisions and has been extended to cover the determination of Speed and Speed Number of both an individual sample and a product as a whole.

A quantity called American Standard Speed Number has been introduced into the standard. It is a rating for a film for use in connection with exposure tables, exposure computers, exposure meters, and similar devices for obtaining properly exposed negatives. It is related to the speed of the material and can be determined from the speed by a formula provided in the standard.

In the American Emergency Standard Photographic Exposure Computer (Z38.2.2-1942), issued March 26, 1942 at the request of the Armed Forces of the United States, it was also necessary to provide a value which, when used in connection with the exposure calculator included in the standard, would insure obtaining suitable negatives. In the American Emergency Standard this value was called Film Exposure Index. When the committee subsequently came to consider a name for this quantity in the present standard, it was concluded that for general civilian use it would be more satisfactory to employ a name indicating that this value was related to speed. The term *American Standard Speed Number* was therefore chosen. The Speed Number, as determined by the methods described in the present standard, may be used directly with the Emergency Standard Computer in place of the Film Exposure Index.

The initials ASA may be used in connection with numerical values of Speed determined in accordance with the complete method.

The words American Standard may be used in connection with numerical values of Speed Number when determined in accordance with the complete method.

Suggestions for improvement based upon experience gained in the use of these methods will always be welcome. They should be sent to the American Standards Association, 29 West 39th Street, New York 18, New York.

The American Standards Association in the past has acted as the secretariat for the project on Photography, ISA 42 of the International Standards Association. A printed draft of this standard, dated December 1, 1940, was circulated for comments to those countries holding membership in ISA Committee 42 and also to the International Congress of Scientific and Applied Photography, which also participates.

The ASA Committee on Standardization in the Field of Photography was initiated in September, 1938, on the recommendation of a general conference of the American photographic industry following a request from the International Standards Association that the ASA accept the secretariat for ISA Committee 42 on Photography. The Optical Society of America was designated as sponsor for the ASA project.

The scope for the ASA project is as follows:

> The formulation of definitions, dimensional standards, and recommended practices in the field of photography, and the establishment of methods for testing, rating, and classifying the performance characteristics of materials and devices used in photography, including its industrial applications, but excluding cinematography.

The membership of the ASA Committee on Standardization in the Field of Photography, Z38, is as follows:

LOYD A. JONES, *Chairman*
J. W. MCNAIR, *Secretary*

* "The Evaluation of Negative Film Speeds in Terms of Print Quality," Loyd A. Jones, Journal of the Franklin Institute **227**, 297 and 497 (1939). "A Study of Various Sensitometric Criteria of Negative Film Speeds," Loyd A. Jones and C. N. Nelson, Journal of the Optical Society of America **30**, 93 (1940).

Organization Represented	*Name of Representative*
Optical Society of America (*Sponsor*)	Raymond Davis
	C. W. Gartlein
	A. C. Hardy
	Loyd A. Jones
	Brian O'Brien
Agfa Ansco—Division of General Aniline & Film Corporation	Paul Arnold
	John Forrest
American Astronomical Society	Fred L. Whipple
American Chemical Society	S. E. Sheppard
American Committee of the International Congress of Photography	Walter Clark
American Geophysical Union	Captain T. J. Maher
American Microscopical Society	Oscar W. Richards
American Optical Company	E. D. Tillyer
	O. W. Richards (*Alternate*)
American Roentgen Ray Society	Fred O. Coe, M.D.
American Society of Photogrammetry	O. M. Miller
American Society for Testing Materials	L. V. Foster
	H. E. Seemann (*Alternate*)
Bausch & Lomb Optical Company	W. B. Rayton
	L. V. Foster (*Alternate*)
Biological Photographic Association	Louis Schmidt
	Leo C. Massapust (*Alternate*)
Cambridge Instrument Company, Inc.	U. O. Hutton
Defender Photo Supply Company, Inc.	Rowland S. Potter
	A. D. Jackling (*Alternate*)
DuPont Film Manufacturing Corporation	D. R. White
Eastman Kodak Company	F. M. Bishop
	V. J. Moyes (*Alternate*)
	M. E. Russell
	Walter Clark (*Alternate*)
Electrical Testing Laboratories	S. McK. Gray
Fairchild Aerial Camera Corporation	George Rattray
	Irving Doyle (*Alternate*)
Folmer Graflex Corporation	Gaylord C. Whitaker
	V. E. Whitman (*Alternate*)
Gevaert Company of America, Inc.	Joseph H. Coenen
Haloid Company	John Dessauer
Interchemical Corporation	George Welp
International Industries, Inc.	C. H. Harris
	W. A. Patton (*Alternate*)
E. Leitz, Inc.	Augustus Wolfman
Lithographic Technical Foundation, Inc.	Paul W. Dorst
National Bureau of Standards, U. S. Department of Commerce	Raymond Davis
National Electrical Manufacturers' Association	J. S. Cowles
	W. N. Goodwin, Jr.
	F. K. McCune
National Photographic Dealers' Association	H. O. Bodine
Photo Utilities, Inc.	Joseph M. Bing
	Walter J. Archinal (*Alternate*)
Photographers' Association of America	William Gerdes
Photographic Society of America	John R. Weber
	F. Quellmalz, Jr. (*Alternate*)

Organization Represented	*Name of Representative*
Radiological Society of North America	F. O. Coe, M.D.
Society of Motion Picture Engineers	J. I. Crabtree
Underwriters' Laboratories, Inc.	A. F. Matson
U. S. Department of Commerce—Coast and Geodetic Survey	Commander O. S. Reading Captain T. J. Maher (*Alternate*)
U. S. Navy Department	Bureau of Aeronautics, Photographic Section, Officer-in-Charge
U. S. War Department—Air Corps	George A. Magnus
U. S. War Department—Signal Corps	Captain Robert F. Nicholson
Universal Camera Corporation	George Kende

Subcommittees have been appointed to develop standards, specifications, and methods of test under the above broad scope which covers the whole photographic field. The assignments of the subcommittees are as follows:

Subcommittee 1—Physical dimensions of sensitive materials, specifically of unexposed, unprocessed, sensitive materials and holders therefor.
Subcommittee 2—Sensitivity to radiant energy.
Subcommittee 3—Supports for sensitive coatings.
Subcommittee 4—Exposing equipment: cameras, lenses, shutters, etc.
Subcommittee 5—Photographic characteristics of illuminants.
Subcommittee 7—Printing and projection equipment.
Subcommittee 8—Processing and processing equipment.
Subcommittee 9—Definitions; abbreviations and symbols; form and arrangement of published standards; numbering of standards.

The Subcommittee on Sensitivity to Radiant Energy, Subcommittee No. 2, which developed this standard on photographic speed, has the following personnel:

M. E. Russell, *Chairman*

Paul Arnold
Joseph M. Bing
Walter Clark
Raymond Davis
John Dessauer
W. N. Goodwin, Jr.
F. K. McCune
Brian O'Brien
Rowland S. Potter
E. D. Tillyer
D. R. White

0. Scope

This method of determining Speed and Speed Number applies to roll films, film packs, and miniature camera films* intended for the making of monochromatic, continuous-tone negatives in pictorial photography, exclusive of photography in the infra-red.

1. Introduction—Discussion of Problem and Explanation of Terms

1.1 Concept of Speed for the Materials in this Specification. The photographic speed of the negative materials referred to in the paragraph "Scope" is to be considered as inversely proportional to the minimum exposure which must be incident upon the negative material, from the scene element of minimum brightness in which detail is visible, in order that a print of excellent quality can be made from the resultant negative. It is understood that the word visible as used in the previous sentence implies visibility of detail from the camera position to a human observer having normal visual acuity and normal sensitivity to brightness differences. It is also understood that this concept of photographic speed presupposes a scene of approximately normal brightness contrast.†

In the field of negative-positive, black-and-white materials, this concept implies that speed can be measured by making the best possible print from each of a series of negatives (which

* Miniature camera films, of the negative-positive, black-and-white type, are considered to be films not more than 35 mm in width, used in still cameras for the making of negatives which normally require enlarged prints.

† Such a normal scene may be characterized with sufficient precision for the present purposes as one in which the ratio of the maximum to the minimum brightness is 128. With a typical camera such as is used in the amateur field, this results in a ratio of maximum to minimum illumination on the negative material in the camera of 32.

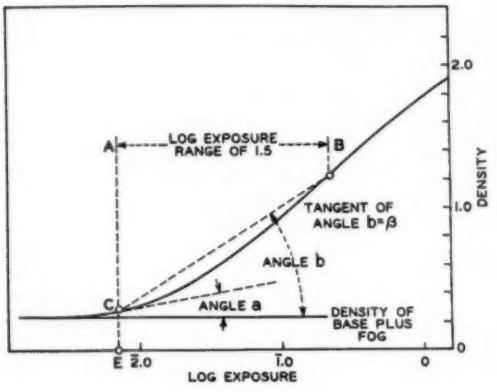


FIG. 1.

differ only in the exposure given) and then deciding by observation the minimum negative exposure that will lead to an excellent print. Speed measured by this psycho-physical method is called Absolute Speed. In practice, it is found difficult to obtain precise values of Absolute Speed, since, in addition to making suitable negatives, many prints must be made and a large panel of judges must make a multitude of observations.

A practical method of measuring speed has been found in the field of sensitometry. The method is reasonably simple and rapid to operate, is reproducible, and gives results in close agreement with those obtained by the laborious process of making picture negatives and prints.

1.2 Sensitometric Criterion of Speed. The operation of this method is illustrated in Fig. 1. Essentially, it consists of plotting the density-log exposure curve of a photographic material for a given set of conditions (exposure, development, etc). A log exposure range of 1.50, represented in the figure by the distance AB, is then moved along the horizontal axis from left to right until the slope (or gradient) of the curve at the low end of the range is 0.30 of the average slope over the entire range. When the slope or tangent of angle a is 0.30 of β (i.e., the tangent of angle b), the point C, at the low end of the log exposure range, represents the exposure value (E) from which the Speed of the material is derived.

Speed is then computed by use of the formula:

$$\text{Speed} = 1/E.$$

The American Standards Association is adopting this sensitometric criterion for determining Speed.

Since several systems for determining speed are quite widely used throughout the world, it is felt that Speed measured by using the American sensitometric criterion should be clearly marked to avoid confusion. This may be accomplished by using the prefix 0. For example, if $1/E$ equals 200, the Speed would be written 0200.

If, in addition to use of the American Standards Association sensitometric criterion for calculating Speed, the American Standards Association testing technique (exposure, processing, etc.) is used, as described in these specifications, then the Speed may be further characterized by use of the initials ASA. For example, a sample of film exposed, processed, and evaluated in strict accordance with the complete method might give a value for Speed which would be written ASA Speed 0200.

Should some factor be varied in the testing technique (that is, in the production of the density-log exposure curve), the initials ASA must not be used. However, as stated above, if the sensitometric criterion has been used, the Speed may still be written with the prefix 0, such as 0160.

1.3 Speed Number.* A Speed Number is the rating of a film for use in connection with exposure tables, exposure computers, and exposure meters. Experience has shown that if the ASA Speed is divided by 4, the numbers resulting will correspond to those now commonly used in exposure tables, exposure computers, exposure meters, and used in common practice. The numbers so derived are called Speed Numbers.

It should be remembered that Speed obtained by the use of these specifications relates to the minimum camera exposure which will lead to an excellent print. In normal photographic work it is customary to recommend a somewhat greater exposure in order to allow for uncertainties in processing, lighting conditions, camera operation, etc. Exposure tables, computers, and exposure meters applying the Speed Numbers are designed to take into consideration this additional ex-

* See the first two paragraphs on page 479, in the Foreword to this standard.

posure. In the case of reversal and color films, however, which are not included in this standard, a different ratio of Speed to Speed Number may apply.

Values of Speed Number are not written with the prefix 0, and consequently are readily distinguishable from values of Speed.

If a Speed Number has been obtained by following the details of this method, it may be characterized by use of the words American Standard Speed Number. In this case a value would be designated thus: American Standard Speed Number 50.

1.4 Speed and Speed Number of a Product. It is possible, and often desirable, to measure the Speed and Speed Number of an individual sample with an uncertainty of not more than 25 percent; hence a cube-root-of-2 scale is used for expressing the values of individual samples of film. In dealing with a product as a whole, it is generally difficult to obtain this accuracy. Moreover, such precision is not particularly significant, considering the large variations to which normal photographic exposing and processing are subject. Therefore, in specifying the Speed and Speed Number of a product, a power-of-2 scale is used.

2. Determination of Speed and Speed Number of a Specific Sample

2.1 Determination of Speed

2.1.1 Speed shall be computed by the use of the formula:

$$\text{Speed} = 1/E,$$

where E is the exposure (expressed in meter-candle-seconds) corresponding to the point on the density-$\log_{10}$ exposure curve at which the gradient is 0.3 times the average gradient for a $\log_{10}$ exposure range of 1.50 of which E is the minimum exposure.

2.1.2 ***Speed Scale.*** Values of Speed shall be expressed arithmetically on a cube-root-of-2 scale. They shall be calculated as described above but shall be rounded off to the nearest cube-root-of-2 step as indicated by Table 1.

2.1.3 Speed shall be written with a prefix 0.

2.1.4 Speeds determined by the above formula are not intended for use with ordinary exposure meters or exposure calculators.

2.2 Determination of Speed Number

2.2.1 Speed Number for the types of photographic materials covered by these specifications shall be determined by use of the formula:

$$\text{Speed Number} = \frac{\text{Speed}}{4}$$

where Speed is computed as specified in 2.1.1.

2.2.2 ***Speed Number Scale.*** Speed Numbers shall be expressed arithmetically on a cube-root-of-2 scale. They shall be calculated as described above but shall be rounded off to the nearest cube-root-of-2 step as indicated in Table 1.

2.2.3 The prefix 0 shall not be used with the Speed Number.

2.3 Testing Technique

2.3.1 ***Conditioning of Sample for Testing.*** The test sample shall be in equilibrium with an atmosphere maintained at a temperature of 20C ± 5 degrees and a relative humidity of 55 ± 5 percent.

2.3.2 ***Exposure***

2.3.2.1 *Type of Sensitometer.* The sensitometer shall be a non-intermittent intensity-scale type.

2.3.2.2 *Exposure Time.** Exposure time shall be between 1/20 and 1/80 second.

2.3.2.3 *Modulation.* The light modulator shall be spectrally non-selective from a wave-length of 350 mμ to a wave-length of 700 mμ.

The change in exposure with distance along the test strip for either continuous or stepped exposures shall be not greater than a factor of 2 per centimeter.

If stepped increments are used, the exposure increment shall be not greater than a factor of square-root-of-2 per step.

2.3.2.4 *Light Source.*† The quality of the light source shall be that defined by the International Congress of Photography in establishing

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* The required illumination depends upon the time of exposure chosen.

† "The Unit of Photographic Intensity," *Proceedings of the Seventh International Congress of Photography*, July 1928. (W. Heffer & Sons, Ltd., Cambridge, England).

Raymond Davis and K. S. Gibson, *Filters for the Reproduction of Sunlight and Daylight and the Determination of Color Temperature*, National Bureau of Standards, Miscellaneous Publication No. 114.

Raymond Davis and K. S. Gibson, "Artificial sunlight for photographic sensitometry," Transactions of the Society of Motion Picture Engineers, **12**, 225 (1928).

the international unit of photographic intensity. The unit of photographic intensity shall be the intensity of a filtered source of radiation having a luminous intensity of one international candle, and produced by a gray body at a color temperature of 2360 degrees Kelvin, together with a selectively absorbing filter made up as follows:

Two solutions compounded according to the following formulas, the complete filter to consist of a one-cm layer of each solution contained in a double cell made by using three pieces of borosilicate crown glass (refractive index, $D=1.51$), each 2.5 mm thick.

Solution *A*

Copper sulfate ($CuSO_4 \cdot 5H_2O$)	3.707 grams
Mannite ($C_6H_8(OH)_6$)	3.707 grams
Pyridine (C_5H_5N)	30.0 cc
Water (distilled) to make	1000.0 cc

Solution *B*

Cobalt ammonium sulfate ($CoSO_4(NH_4)_2SO_4 \cdot 6H_2O$)	26.827 grams
Copper sulfate ($CuSO_4 \cdot 5H_2O$)	27.180 grams
Sulfuric acid (sp gr 1.835)	10.0 cc
Water (distilled) to make	1000.0 cc

The light transmission of the filter to 2360 degrees Kelvin radiation is 13.52 percent.

An alternative source and filter may be a tungsten lamp operated at a color temperature of 2660 degrees Kelvin and screened by a Davis-Gibson liquid filter made up as follows:

Two solutions compounded according to the following formulas, the complete filter to consist of a one-cm layer of each solution contained in a double cell made by using three pieces of borosilicate crown glass (refractive index, $D=1.51$), each 2.5 mm thick.

Solution *A*

Copper sulfate ($CuSO_4 \cdot 5H_2O$)	2.874 grams
Mannite ($C_6H_8(OH)_6$)	2.874 grams
Pyridine (C_5H_5N)	30.0 cc
Water (distilled) to make	1000.0 cc

Solution *B*

Cobalt ammonium sulfate ($CoSO_4(NH_4)_2SO_4 \cdot 6H_2O$)	20.145 grams
Copper sulfate ($CuSO_4 \cdot 5H_2O$)	21.98 grams
Sulfuric acid (sp gr 1.835)	10.0 cc
Water (distilled) to make	1000.0 cc

The light transmission of the filter to 2660 degrees Kelvin radiation is 20.9 percent.

Table 1.

For a $\log_{10} E$ value between*	Speed $(1/E)$	Speed Number
(6.35–10) and (6.45–10)	04000	1000
(6.45–10) and (6.55–10)	03200	800
(6.55–10) and (6.65–10)	02500	650
(6.65–10) and (6.75–10)	02000	500
(6.75–10) and (6.85–10)	01600	400
(6.85–10) and (6.95–10)	01250	320
(6.95–10) and (7.05–10)	01000	250
(7.05–10) and (7.15–10)	0800	200
(7.15–10) and (7.25–10)	0650	160
(7.25–10) and (7.35–10)	0500	125
(7.35–10) and (7.45–10)	0400	100
(7.45–10) and (7.55–10)	0320	80
(7.55–10) and (7.65–10)	0250	64
(7.65–10) and (7.75–10)	0200	50
(7.75–10) and (7.85–10)	0160	40
(7.85–10) and (7.95–10)	0125	32
(7.95–10) and (8.05–10)	0100	25
(8.05–10) and (8.15–10)	080	20
(8.15–10) and (8.25–10)	064	16
(8.25–10) and (8.35–10)	050	12
(8.35–10) and (8.45–10)	040	10
(8.45–10) and (8.55–10)	032	8
(8.55–10) and (8.65–10)	025	6
(8.65–10) and (8.75–10)	020	5
(8.75–10) and (8.85–10)	016	4
(8.85–10) and (8.95–10)	012	3
(8.95–10) and (9.05–10)	010	2.5
(9.05–10) and (9.15–10)	08	2.0
(9.15–10) and (9.25–10)	06	1.6
(9.25–10) and (9.35–10)	05	1.2
(9.35–10) and (9.45–10)	04	1.0
(9.45–10) and (9.55–10)	03	0.8
(9.55–10) and (9.65–10)	02.5	0.6

* When the log E value is exactly on the border line of two groups, the group giving the lower value of Speed shall be used.

2.3.3 *Processing*

2.3.3.1 *Roll Films and Film Packs.* The processing shall be commenced within 1 hour after exposure. Fresh solutions shall be used.

2.3.3.1a *Developing Solution*

*Monomethyl para-aminophenol sulfate	2.0 grams
Sodium sulfite (anhydrous)	50.0 grams
Hydroquinone	4.0 grams
Sodium carbonate (anhydrous)	6.0 grams
Potassium bromide	0.75 gram
Air-free distilled water to make	1.0 liter

2.3.3.1b *Agitation.* The agitation given the test sample during development shall be equivalent to that produced by the following method:

The developer is poured into a vacuum flask having an internal length of approximately 22 cm and an internal diameter of about 4 cm. The developer is added until three-quarters of the

* Sold under such trade names as Metol, Elon, Rhodol, and Pictol.

free space is filled. The negative material to be tested is fastened by means of rubber bands to a glass strip having a width of about 3.5 cm and a length of about 20 cm. The glass strip is fixed to an inert stopper and projects into the flask when the stopper is in place. The stopper carrying the glass strip and test films is inserted in the flask and the development is carried out at the prescribed temperature. During development the vessel is given an oscillatory movement by tilting it in a vertical plane to an angle of about 45 degrees above and below the horizontal. The rate is such that one complete cycle is made in about 1 second. At the same time the vessel is revolved about its axis, the time for one revolution being about 5 seconds. To terminate development, the films are withdrawn and immediately immersed in the fixing bath.

2.3.3.1c *Extent of Development.* The temperature of the developing solution shall be 20C±0.5 degrees. The time of development shall be 4.0 minutes, providing the average gradient (designated by the Greek letter β) for the $\log_{10}$ exposure range from which the Speed is determined is not less than 0.50. If the value of β is less than this minimum, the time of development shall be extended to produce a value of β equal to 0.50.

2.3.3.1d *Fixing.* The test samples shall be immersed in the following fixing bath immediately after development:

Sodium thiosulfate (Hypo)	250 grams
Sodium sulfite (desiccated)	10 grams
Sodium bisulfite	25 grams
Water to make	1 liter

The fixing solution shall be held at 20C±5 degrees and the fixing time shall be approximately 15 minutes.

2.3.3.1e *Washing.* Washing shall be done in water at 20C±5 degrees.

2.3.3.1f *Drying.* The samples shall be dried in evenly circulated air maintained at a temperature of 20C±5 degrees.

2.3.3.2 *Miniature Camera Films.* The processing shall be commenced within 1 hour after exposure. Fresh solutions shall be used.

2.3.3.2a *Developing Solution*

*Monomethyl para-aminophenol sulfate	2.0 grams
Sodium sulfite (anhydrous)	80.0 grams
Hydroquinone	4.0 grams
Borax	4.0 grams
Potassium bromide	0.5 gram
Air-free distilled water to make	1.0 liter

*Sold under such trade names as Metol, Elon, Rhodol, and Pictol.

2.3.3.2b *Agitation.* Same as for Roll Films and Packs (2.3.3.1b).

2.3.3.2c *Extent of Development.* The temperature of the developing solution shall be 20C±0.5 degrees. The time of development shall be 8.0 minutes, providing the average gradient (designated by the Greek letter β) for the $\log_{10}$ exposure range from which the Speed is determined is not less than 0.50. If the value of β is less than this minimum, the time of development shall be extended to produce a value of β equal to 0.50.

2.3.3.2d *Fixing.* Same as for Roll Films and Packs (2.3.3.1d).

2.3.3.2e *Washing.* Same as for Roll Films and Packs (2.3.3.1e).

2.3.3.2f *Drying.* Same as for Roll Films and Packs (2.3.3.1f).

2.3.4 ***Density.*** Density shall be computed from the formula:

$$\mathbf{D} = \log_{10} \frac{1}{T}$$

where T is the diffuse transmission of the processed sample.

2.3.5 ***Accuracy.*** The accuracy of the testing procedure (as specified under 2.3) shall be such that the probable error of the Speed or the Speed Number shall not exceed plus or minus one-half cube-root-of-2 step (i.e., ±13 percent).

2.3.6 Values of Speed determined by following the complete procedure described in this standard may be characterized by use of the initials ASA, e.g., ASA Speed 0200.

2.3.7 Values of Speed Number determined by following the complete procedure described in this standard may be characterized by use of the words American Standard, e.g., American Standard Speed Number 50.

3. Determination of Speed and Speed Number of a Product

3.1 The Speed of a Product (as distinguished from that of a specific sample) shall be the

numerical average of the Speeds of a number of individual samples of the product, these samples being selected, stored, and tested as specified in 3.3, 3.4, and 3.5 below.

The average figure shall be rounded off to the nearest power-of-2 step, using the Speed scale in Table 2.

3.2 The Speed Number of a Product, for the classes of photographic materials covered by this method, shall be determined by use of the formula:

$$\text{Speed Number of the Product} = \frac{\text{Speed of the Product}}{4}.$$

The value shall be rounded off to the nearest power-of-2 step, using the scale given in Table 2.

3.3 Sampling. At least three sets of samples shall be tested, taken at approximately 1-month intervals. The total number of samples of the three groups shall be such that the probable error of the average Speed is not greater than plus or minus one-half a power-of-2 step. In no case shall less than twelve samples be used for testing any product. The samples should be obtained from the plant of the manufacturer, or from an accredited distributor if they cannot be obtained directly from the manufacturer.

Table 2.

Average of Speeds of Individual Samples*	Speed (1/E)	Speed Number
04500 to 02250	03200	800
02250 to 01125	01600	400
01125 to 0560	0800	200
0560 to 0280	0400	100
0280 to 0140	0200	50
0140 to 070	0100	25
070 to 035	050	12
035 to 018	025	6
018 to 09	012	3
09 to 04.5	06	1.6
04.5 to 02.2	03	0.8

* When the average Speed value is exactly on the border line of two groups, the group giving the lower value of Speed shall be used.

3.4 Storage of Samples. All samples which are to be used in making the tests shall be stored at 20C±5 degrees and at a relative humidity of 55±5 percent for a period of 3 months after procurement from the manufacturer or distributor.

3.5 Testing. At the end of the above keeping period, each sample shall be tested and its Speed determined according to the method set forth in Section 2 of this standard ("Determination of Speed and Speed Number of a Specific Sample").